GENETIC ADAPTIVE SEARCH FOR PHOSPHORUS PREDICTION IN OXYGEN STEEL MAKING

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CERTIFICATE

It is certified that the work contained in the thesis entitled **Genetic Adaptive Search for Phosphorus Prediction in Oxygen Steel making**, by **Veluru Sudhakar**, has been carried out under our supervision and that this work has not been submitted elsewhere for a degree.

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ABSTRACT

Partitioning of phosphorus between slag and metal depends upon basicity, FeO content of slag and temparature. Ionic theory of slag and its application to predict phosphorus distribution between slag and metal in oxygen steel making converters is briefly reviewed. Several empirical correlations for predicting phosphorus at end point are devloped on the basis of published operational data. Both genetic adapive search (GAS) and multiple linear regression (MLR) are used as optimization techniques to decide the most suitable correlation. Basic priniciples of GAS are explained.

Dedicated to

my Father

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Veluru Sudhakar

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a_C	:	Activity of carbon
a_{FeO}	:	Activity of FeO
a_{Fe}	:	Activity of Fe
a_{CaO}	:	Activity of CaO
$a_{P_2O_5}$	:	Activity of P_2O_5
$C_{PO_4^{3-}}$	:	Phosphate capacity
C_i	:	Coefficients ($i = 1 \ldots 5$)
e_P^x	:	Phosphorus interaction prameter
f_P	:	activity coefficent of P
Fe_t	:	Fe theoritical
K_3, K_4	:	Equilibrium constants
L_P	:	Phophorus partition
N'_{Ca}	:	Equivalent ion fraction for calcium
N'_O	:	Equivalent ion fraction for oxygen
N'_{Fe}	:	Equivalent ion fraction for iron
N'_{PO_4}	:	Equivalent ion fraction for phosphate
P_{O_2}	:	Oxygen partial pressure
P_{cr}	:	Crossover probability

P_m	:	Mutation probability
R	:	Regression coefficient
T	:	Temperature
V_{O_2}	:	Volume of oxygen
W_{ore}	:	Weight of ore added
ΔG^o	:	Free energy
σ	:	Standard deviation
$(\%P)$	:	Phosphorus in slag
$[\%P]$	:	Phosphorus in steel

Chapter 1

Introduction

The high percentage of continuous casting possibly brings out serious problems caused by central segregation, particularly segregation of phosphorus, which causes hydrogen-induced cracking and heat-effect zone cracking in welding. In order to avoid these problems, the concentration of phosphorus in the steel should be reduced.

In the last forty years of oxygen steel making many interesting theories like molecular theory of slag, optical basicity and ionic theory of slag, and also empirical correlations have been proposed to predict phosphorus at end point. Since ionic theory of slag has been most successful, its application to predict phophorus distribution in steel making is briefly reviewed in chapter 2. Healy's equation [1] based on ionic theory of slag is frequently used to predict the phosphorus equilibrium. In the present work genetic adaptive search (GAS) is used for the first time to optimize Healy's equation. Working principles of GAS are explained in Chapter 3. Various empirical correlations (based on Healy's equation) are optimized and tested on actual operational data in chapter 4. An important term in phosphorus prediction is FeO content

of slag. Various options to predict FeO content of slag are also evaluated in Chapter 4. Conclusions and extensions possible in this study are discussed in chapter 5.

Chapter 2

Ionic theory of slag for phosphorus prediction in steel

2.1 Introduction

The prediction of equilibrium distribution of phosphorus between slag and metal is generally based on ionic theory of slag. In this chapter application of ionic theory of slag to predict phosphorus distribution between slag and metal is briefly reviewed.

2.2 Application of ionic theory of slag for phosphorus distribution

The dissolution of phosphorus in liquid iron can be represented as,

$$\frac{1}{2}P_{2(g)} \rightarrow [P_{\%}] \qquad \Delta G^o = -122173 - 19.25T, J \tag{2.1}$$

In the presence of other solutes the activity coefficient for phosphorus (f_P) is calculated from

$$Log f_P = \sum e_P^X \times \%X \tag{2.2}$$

where e_P^X is the interaction coefficient. Carbon and silicon have a positive interaction coefficient; the published values of interaction parameter e_P^C range from 0.09 to 0.14 at 1600^oC while for silicon (e_P^{Si}) the range is 0.09-0.18.

In slags the dissolution of phosphorus is more complex. The basic oxides liberate oxygen ions,

$$CaO = Ca^{++} + O^{--} \tag{2.3}$$

$$FeO = Fe^{++} + O^{--} \tag{2.4}$$

$$Fe_2O_3 = 2Fe^{3+} + 3O^{-} \tag{2.5}$$

while acidic oxides consume oxygen ions,

$$P_2O_5 + 3O^{--} = 2PO_4^{3-} \tag{2.6}$$

$$SiO_2 + 2O^{--} = SiO_4^{4-} \tag{2.7}$$

$$Al_2O_3 + 3O^{--} = 2AlO_3^{3-} \tag{2.8}$$

The electrically equivalent ion fraction (N') of anions and cations is obtained from

$$N'_{Ca} = \frac{\text{mol}CaO/100g \text{ slag}}{\text{total positive charges}/100g \text{ slag}} \tag{2.9}$$

$$N'_{PO_4} = \frac{\text{mol}P/100g \text{ slag}}{\text{total negative charges}/100g \text{ slag}} \tag{2.10}$$

knowing the equilibrium constants and electrically equivalent ion fractions, the activity of P_2O_5 and CaO can be claculated. If the overall dissolution reaction is written as

$$P_2 + \frac{5}{2}O_2 + 3O^{2-} = 2PO_4^{3-} \tag{2.11}$$

then the equlibrium constant becomes

$$K_3 = \frac{\left(a_{PO_4^{3-}}\right)^2}{P_{p_2} PO_2^{2.5} a_{O^{2-}}^3} \qquad (2.12)$$

In order to calculate K_3, the oxygen and phosphate ion activities are needed. Since single ion activities can not be measured, Wagner[2] defined phosphate capacity of slag as

$$C_{PO_4}^{3-} = \frac{\left(\%PO_4^{3-}\right)}{\sqrt{P_{n_2}} P_{O_2}^{1.25}} \qquad (2.13)$$

From Eq.(2.12) and Eq.(2.13)

$$C_{PO_4}^{3-} = \frac{a_{O^{2-}}^{1.5}}{f_{PO_4^{3-}}} \sqrt{K_3} \qquad (2.14)$$

Phosphate capacity is thus a measure of the dephosphorizing ability of slag under given oxygen potential and is related to the oxygen ion activity of the slag (or basicity of slag).

Some workers have proposed alternative definitions of the phosphate capacity,

$$C_p = \frac{(\%P_2O_5)}{[a_p][a_o]^{2.5}} \qquad (2.15)$$

and

$$C_{PO_4^{3-}}^{1} = \frac{X_{PO_4^{3-}}}{[\%P]\left(X_{FeO}\right)^{2.5}} \qquad (2.16)$$

From practical purposes, partitioning of phosphorus between slag and metal is represented as a ratio (L_P)

$$L_P = \frac{(\%P)}{[\%P]} \quad \left(or \frac{(\%P_2O_5)}{[\%P]}\right) \qquad (2.17)$$

In principle, from the knowledge of the processing conditions, a relationship between the phosphorus partition (L_P) and the phosphate capacity can be derived. One of the major obstacles is the calculation of equilibrium oxygen partial pressure, which can be defined in several ways.

2.2.1 Melts with high carbon content

Oxygen partial pressure is derived from the carbon, oxygen, carbon monoxide equilibrium

$$C + \frac{1}{2}O_2 \rightarrow CO: \qquad \Delta G^o = -114.28 - 0.085T, kJ \tag{2.18}$$

$$K = \frac{CO}{a_c\sqrt{pO_2}} \tag{2.19}$$

For carbon saturated iron at 1300°C, $pO_2 = 2.4 \times 10^{-17}$ atm.

For carbon activity of 0.8 at 1300°C, $pO_2 = 3.76 \times 10^{-17}$atm.

2.2.2 Slags containing ferrous oxide

$$Fe_{(1)} + \frac{1}{2}O_2 \rightarrow FeO_{(1)}: \qquad \Delta G^o = -264.64 + 0.065T, kJ \tag{2.20}$$

at 1600°C, $pO_2 = 10^{-8}(a^2_{FeO})$ atm.

2.2.3 Oxygen dissolved in steel

$$\frac{1}{2}O_2 \rightarrow [O_{\%}]: \qquad \Delta G^o = -117 - 0.0029T, kJ \tag{2.21}$$

at 1600°C, $pO_2 = 1.38 \times 10^{-7}[\%O]^2$ atm.

In the case of carbon saturated melts phosphorus partition can be represented as

$$log\frac{(\%P)}{[\%P]} = logC_{PO_4^{3-}} - \frac{21394}{T} - 12.73 + logf_P + \left(2.5log\frac{P_{CO}}{a_c}\right) \quad (2.22)$$

Similarly, for slags containing FeO,

$$log\frac{(\%P)}{[\%P]} = logC_{PO_4^{3-}} - \frac{41113}{T} + 7.06 + 2.5loga_{FeO} + logf_P \quad (2.23)$$

If a_{FeO} is expressed in terms of oxygen content of metal then Eq.2.21 becomes

$$log\frac{(\%P)}{[\%P]} = logC_{PO_4^{3-}} - \frac{21744}{T} - 1.865 + 2.5log[\%O] + logf_P \quad (2.24)$$

a_{FeO} can also be expressed in terms of both carbon and oxygen content of steel.

2.3 Healy's equation for phosphorus partition

Instead of Eq(2.11), Healy[1] considerd the overall reaction for phosphorus distribution in lime saturated slags as

$$\begin{aligned} 2[P] + 5(FeO) + 4(CaO) &= (Ca_4P_2O_9) \quad (2.25) \\ \Delta G_2^o &= -204450 - 83.55T, J \end{aligned}$$

The equilibrium constant for Eq.(2.26) can be written as,

$$K_4 = \frac{a_{Ca_4P_2O_9}}{[P]^2 a_{FeO}^5 a_{CaO}^4} \quad (2.26)$$

Considering that metallic oxides are present in their standard states, P_2O_5 is choosen such that $a_{P_2O_5} = 1$, when $a_{Ca_4P_2O_9}$ and a_{CaO} both are equal to one, then

$$K_4 = \frac{a_{P_2O_5}}{[P]^2 a_{FeO}^5} \quad (2.27)$$

$$\log K_4 = \frac{44700}{T} - 18.26 \tag{2.28}$$

It can be shown that

$$a_{P_2O_5} = \frac{1}{36a_{CaO}^{3.7}} \times \frac{(N'_{PO_4})^2}{(N'_O)^3} \tag{2.29}$$

$$\log a_{CaO} = 3.8(logN'_{Ca} + logN'_O + logK'_{CaO,sat}) \tag{2.30}$$

Equation for estimating the phosphorus distribution therefore becomes,

$$\begin{aligned}\frac{44700}{T} - 18.26 &= 2logN'_{PO_4} - 3logN'_O - log36 - 3.7(\log N'_{Ca} + logN'_O + \\ &\quad logK'_{CaO,sat.}) - 2\log[P] - 5(logN'_{Fe} + logN'_O \\ &\quad +logK'_{FeO})\end{aligned} \tag{2.31}$$

On rearranging the terms, the final equation for dephosphorization, as proposed by Healy, becomes

$$\log\frac{(\%P)}{[\%P]} = \frac{22350}{T} + 7\ \ log(\%CaO) + 2.5\log(\%Feo) - 16.0 \tag{2.32}$$

In industry, the coefficients of above equation are tuned to actual practice. Some adapted versions of Healy's equation are shown in Table 2.1[3]. It may be noted that each equation in Table 2.1 is valid for specific operating conditions only.

In a recent work Zhang et.al.[4] proposed another equation for dephosphorization by considering the overall reaction as,

$$2[P] + 5[O] + 3O^{2-} = 2(PO_4^{3-}) \tag{2.33}$$

Table 2.1: Phosphorus Distribution Equations

$\log \frac{(\%P)}{[\%P]} =$

(1) $5.9 \log(\%CaO) + 2.5 \log(\%FeO) + 0.5 \log(\%P_2O_5) - 0.0045Fe_t - 3.483$

(2) $5.6(\%CaO) + 2.5log(\%Fe_t) - 21.88 + \frac{22350}{T}$

(3) $0.056(\%CaO) + 2.5 \log(\%Fe_t) + 0.5log(\%P_2O_5) - 10.42 + \frac{12000}{T}$

(4) $5.6log(\%CaO + 0.3\%MgO + CaF_2) + 2.5log(\%FeO) + 0.5log(\%P_2O_5)$
$- 10.1 + \frac{10365}{T}$

(5) $5.9 \log \%CaO + 2.5log\%FeO + 0.5 \log(\%P_2O_5) - 10.82 + \frac{15340}{T}$

(6) $4.11 \log(\%CaO + 0.3\%MgO + CaF_2 - 0.05\%FeO) + 2.5log(\%FeO)+$
$0.5 \log(\%P_2O_5) - 13.87 + \frac{10730}{T}$

(7) $0.067 [\%CaO + 1.6\%Na_2O] + 2.5 \log(\%Fe_t) + \frac{7920}{T} - 8.09$

$\log \frac{(\%P_2O_5)}{[\%P]^2(\%Feo)^5} =$

(8) $7.78 \log [\%CaO + 1.2(\%Na_2O) + 0.3(\%MgO) + 0.9(\%BaO) - 0.5(\%P_2O_5)]$
$-0.05(\%FeO_t) + \frac{22240}{T} - 27.124$

(9) $8.67 \log(\%Na_2O) - 14.55$ at 1600^oC

Some additional terms were incorporated to account specially for the influence of MgO, MnO and SiO_2 content of slag

$$log\frac{(\%P_2O_5)}{[\%P]} = \frac{11000}{T} + 2.5 \ log(\%Feo) + \frac{1}{T}(162(\%CaO) + 127.5(\%MgO) +28.5(\%MnO)) - 6.28X10^{-4}(\%SiO_2)^2 - 10.40 \quad (2.34)$$

In the present work Healy's equation (2.32), which can be adapted to a wide variety of operating conditions, will be optimized.

Chapter 3

Genetic algorithms

3.1 Introduction

Genetic algorithms (GAs) were developed by John Holland and his colleagues at the university of Michigan in 1965. GAs are adaptive search and optimization algorithms based on the mechanics of natural selection and natural genetics [5]. They are robust in complex search spaces and Genetic algorithms do not need any information like continuity, existence of derivatives, and unimodality and other matters.

Genetic algorithms require the natural parameter set of the optimization problem to be coded as a finite length string over some finite alphabet because they manipulate decision or control variable representations at the string level to exploit similarities among high performance strings. Other methods usually deal with functions and their control variables directly. One of the advantages of working with a coding of variable space is that the coding discretizes the search space, even though the function may be continuous. A discrete or continuous function may be tackled using GAs because

it requires function values only at discrete points.

In most optimization methods we move from one point in the search space to the other by some rule. This point to point mehtod may result in locating a local optima in a multi-modal search space. In contrast, GAs work with a population which represent a number of points in the search space. This increases the posibility of obtaining the global optima solution even in ill-behaved problems [6].

Many search techniques require auxiliary information to direct their search. For example, gradient techniques require derivatives in order to search to find optima. However GAs do not require any such kind of information. They remain general by exploiting information available in any search direction. To perform an effective search, they require only payoff values associated with individual strings.

The basic problem with most of the traditional methods is that they use fixed transition rules to move from one point to another. So these methods can be applied only to special class of problems where any point leads to the desired optimum. That is why these methods are not robust and can not be applied to a wide variety of problems. GAs use probabilistic rules to guide their search to reach optimal point.

In this cahpter, essentially adapted from reviews of Deb, 1995,[9] Goldberg, D.E 1989,[5] working principles of GAs are briefly explained.

3.2 Working principle

Pseudo-code for a genetic algorithm is shown in Fig.3.1. GAs begin with a population of strings created randomly. Thereafter, each string in the population is evaluated. The population is then operated by three main operators reproduction, crossover and mutation to create a better population. The population is further evaluated and tested for termination. If the termination criteria are not met, the population is again operated by the above three operators and evaluated. This procedure is continued until the termination criteria are met. One cycle of these operators and the evaluation procedure is known as a *generation* in GA terminology.

```
Begin
    Initialize population;
    Evaluate population;
    repeat
            Reproduction;
            Crossover;
            Mutation;
    until (termination criteria);
End.
```

Figure 3.1: A pseudo-code for a simple genetic algorithm

3.2.1 Strings

Genetic algorithm starts with initialization of strings. These strings of artificial genetic systems are analogous to chromosomes in biological systems. The chromosomes are composed of genes which take some number of values called alleles. Similar to the genes in the natural chromosomes which influence the physical properties of an

individual, the values of 1 or 0 in each position of a binary string influence the coordinates of a point in search space as each string represents all the problem variables in the optimization problem considered.

The strings in the initial population of GA can be created by tossing of an unbiased coin. The successive coin flips (head=1, tail=0) can be used to decide genes in a string. This procedure is continued till all the strings are generated in the initial random population. The String length for a string, i.e. the total number of bits (genes) is equal to the sum of the bits assumed for each of the problem variables in the optimization problem. The number of bits for a variable depends on the precision required.

3.2.2 Coding and decoding of variables

GAs work with coding of variables instead of variables themselves. A successful method of coding multi parameter optimization problems of real parameters is the concatenated, multi parameter, mapped fixed-point coding. In multivariable optimization, all the problem variables are coded in a single string and each variable has a specific location in the string. Binary coding is most commonly used in GA applications. The precision of problem variables depends on the number of bits assumed for them in the string and the actual range in which they vary.

A string represents a point in the space and the decoded values of the string's contents will represent the coordinates. For example, if an integer variable varies

from 10 to 41, it can be completely represented by a five digit string which can give 32 unique strings. The decoded value for string 00000 is 0, where as the decoded value for 11111 is 31, remaining all strings will have decoded values in between 0 and 31. Consider a string 10100. The decoded value for this string is $(0 \times 2^0 + 0 \times 2^1 + 1 \times 2^2 + 0 \times 2^3 + 1 \times 2^4)$ i.e. 20.

3.2.3 Evaluation

The decoded values from a string varies 0 to 2^l where l is the number of bits in the string. However, the actual values may not vary in that range. Then, the decoded values obtained from the strings should be mapped in the range in which the actual values will vary. Once all the variables are decoded they should be mapped as given below. Let ll and ul be the actual lower and upper bounds in which a variable vary and dc be the decoded value of the string. The mapped value is then given by the following equation.

$$\text{Mapped value} = ll + \frac{(ul - ll) \times dc}{2^l - 1} \tag{3.1}$$

The precision of the variable is $\frac{(ul-ll)}{2^l-1}$

After all the variables are mapped, they can be used to calculate the objective function value (also called fitness value). In this way, all the fitness values for all the strings in a particular generation are calculated. Then the termination criteria is checked. If the termination criteria is not reached, the GA operators are applied on the present population to get a new set of population.

3.2.4 GA operators

Genetic algorithms operate on population of strings, with the string coded to represent some underlying parameter set. A simple genetic algorithm that yields good results in many practical problems is composed of three operators; Reproduction, Crossover and Mutation, which are applied to successive string populations to create new string populations. These operators are very simple involving nothing more than random number generation, string copying and partial string exchanging. Despite their simplicity, the resulting search performance is wide ranging and impressive. These three operators are described below.

Reproduction

Reproduction is the first operator applied on a population. It is a process in which individual strings are copied according to their objective function values. Copying strings according to their fitness values means that the strings with a better value will have a higher probability of contributing one or more strings in the next generation. The operator is an artificial version of natural selection, a Darwinian survival of the fittest among string structures. The best string in the present generation will get more copies , the average stay even and the worst will die off in the next generation. It selects good strings in the population and forms a mating pool. There exists a number of reproduction operators in GA literature, but the essential idea is that above-average strings are picked from the population and duplicates of them are inserted in the mating pool. Several selection schemes are in use today, and a detailed comparative

analysis is made in [6]. The Tournament selection operator has been used in our study and is described below.

3.2.5 Tournament selection

In Tournament Selection, some strings are picked at random and the better string is copied to the mating pool. This process is repeated till the required number of individuals equal to the population size are selected. The number of individuals considered for the selection of an individual is known as *Tournament size.* A tournament size of 2 is used generally in many applications and the same is used in our study. In this selection, two individuals are chosen at random in the current population and the better of them is selected with fixed probability ranging from 0.5 to 1.0. The strings thus selected by reproduction are kept in mating pool for applying the next operator, Crossover. Tournament selection can be used for both minimization and maximization problems without any transformation of the objective function.

Crossover

Crossover operator is applied next to the reproduction of strings in the mating pool. After reproduction, the population is enriched with good strings from the previous generation, but does not have any new string. Crossover operator is applied to the population hopefully to create better strings. There exists a number of crossover operators like single point crossover, multi point crossover, and uniform crossover. In all these operators, two strings are picked from the mating pool at random and some

portion of strings are exchanged between the strings. In the single point crossover, this is performed by choosing a random site along the string and by exchanging all bits to the right of the crossing site as shown below.

$$\begin{array}{ccc} 101|11 & & 101|00 \\ & \Longrightarrow & \\ 111|00 & & 111|11 \end{array}$$

The crossover operator searches the parametric space by exchanging the information between two strings. The strings selected for applying crossover operator are called the parent strings and the strings obtained after crossover are known as child strings. In order to preserve with some of the good strings found previously, crossover is usually performed on only some of the strings in the mating pool. The total number of strings to be participated in crossover is controlled by the *Crossover probability*, which is the ratio of total number of strings selected for mating and the population size. The crossover probability is usually kept high, which varies from 0.90 to 0.95 in many applications.

If appropriate site is selected, good child strings are obtained. However, as this site is not known beforehand, a random site is selected. With random site, the child strings may or may not be good. If the string is good, it is selected. The bad strings created may not survive beyond next generation due to the application of reproduction operator in the next generation. Crossover operator is mainly responsible for the search aspect of genetic algorithm.

Mutation

Mutation plays a secondary role in the operation of Genetic algorithm. It is needed because, even though reproduction and crossover efficiently exploit the search space, sometimes they lose some potentially useful genetic material (1's or 0's at particular locations). Mutation operator changes a 1 to 0 and vice versa with a small *Mutation probability*. The need for mutation is to keep diversity in the population. It is done bit-by-bit basis. Since this operator disrupts a string, the mutation probability is kept very low.

Mutation can be best explained with the help of the following example. Consider a population of size four. Let the strings be

0110

0010

0100

0100

Let the optimal string be 1111. By reproduction and crossover we will never be able to get the optimal string. But mutation may bring 1 in the last position of 1110 resulting in 1111. Then finally the problem will converge to the string 1111.

After applying the GA operators, a new set of population is created. Then, they are decoded and objective function values are calculated. This completes one generation of GA. Such iterations are continued till the termination criteria are reached.

3.2.6 Termination criteria

When the average fitness of all the strings in a population is nearly equal to the best fitness, the population is said to have converged. When the population is converged, the GA is terminated. The same can be done by fixing maximum number of generations, the number of generations at which population will converge. In genetic algorithms, maximum number of generations is generally used as the termination criteria. The same is used in the present study.

3.3 Differences with traditional methods

Genetic algorithms are different from traditional optimization methods in following respects [5].

1. GAs work with a coding of the parameter set, not the parameters themselves.
2. GAs search from a population of points, not from a single point.
3. GAs use payoff (objective function) information, not derivatives or other auxiliary knowledge.
4. GAs use probabilistic transition rules, not deterministic rules.

Chapter 4

Prediction of end point phosphorus in a combined blown converter

4.1 Introduction

As discussed in chapter 2, Healy's equation is widely used in steel industry for prediction of phosphorus in steel. It contains five terms: %CaO, Fe_t, temparature, [%P] in metal and (%P) in slag. Only temperature and [%P] in metal are directly measured.The method of estimation of mass of steel, mass and composition of slag is explained in section 4.2 followed by optimization of Healy's equation by MLR and GAS in section 4.3.

4.2 Estimation of relevant terms in Healy's equation

4.2.1 Estimation of mass of Steel

The iron content of various inputs/outputs is as follows,

- 99.5% Fe from scrap.
- all Fe from ore addition(Fe_2O_3). (assumed)
- 15% Fe present in return slag. (assumed)
- mass of hot metal charged and composition are known and hence Fe from hot metal can be determined.
- Fume loss (55.5Kg Fe/ton of hot metal(THM)).
- Steel is assumed to be 100% Fe (for the sake of simplicity).

Thus,

W_{steel} = Total iron charged - iron loss in slag - iron loss in fumes

4.2.2 Estimation of mass and composition of slag

If the mass of hot metal ($W_{hotmetal}$), scrap (W_{scrap}) and steel (W_{steel}) are known then mass of $W_{P_2O_5}$ in slag is given by (%P from other sources is nearly constant)

$$\begin{aligned} W_{P_2O_5} &= (W_{hotmetal} \times \%P\text{in hot metal} + W_{scrap} \times \%P\text{in scrap} \\ &\quad - W_{steel} \times \%P\text{in steel}) \times \frac{142}{62} \end{aligned} \tag{4.1}$$

Suppose only CaO, P_2O_5, SiO_2, and FeO are considerd to be essential components of slag. Mass of lime charged (W_{CaO}) is known from operational data. Similarly % FeO in slag is known from dynamic model (or sublance measurement of carbon, temperature and oxygen, see section 4.2.3). Mass of slag is then given by (assuming

that other oxides present in the slag are nearly constant)

$$W_{slag} = \frac{W_{CaO} + W_{P_2O_5} + W_{SiO_2}}{1 - \frac{\%FeO}{100}} \tag{4.2}$$

where W_{SiO_2} is known from silica balance (by assuming that all the silicon charged is oxydized to SiO_2). $W_{P_2O_5}$ is obtained from Eq.(4.1). Once W_{slag} is known %CaO and $\%P_2O_5$ ican be calculated. The method of calculation of %FeO is explained below.

4.2.3 Estimation of Fe_t in slag

The iron oxide content can be estimated through the knoweldge of oxygen activity and temparature. The oxygen activity depends on end point carbon and temparature of the steel. The equations are as follows[8, 14],

$$\%FeO = 0.0121 a_O + \frac{150211.2}{T} - 67.08 \tag{4.3}$$

The oxygen activity can be substituted from

$$\log(a_O) = -1.053 \log[\%C] - \frac{5593.3}{T} + 4.119 \tag{4.4}$$

If the coefficients of above equations have to be tuned to actual practice at a particular plant, then the objective function becomes

$$\%FeO = C_1 + C_2\, exp\left(C_3 \log[\%C] - \frac{C_4}{T}\right) + \frac{C_5}{T} \tag{4.5}$$

Multiple linear regression was applied to operational data and the following equation was obtained,

$$\%FeO = -35.94 + 5.72\, exp\left(-1.05 log\,[\%C] - \frac{5593.3}{T}\right) + 0.60\frac{150211.2}{T} \tag{4.6}$$

$$\sigma = 2.80$$

$$R = 0.74$$

Fig(4.1) shows the plot of actual versus predicted FeO.

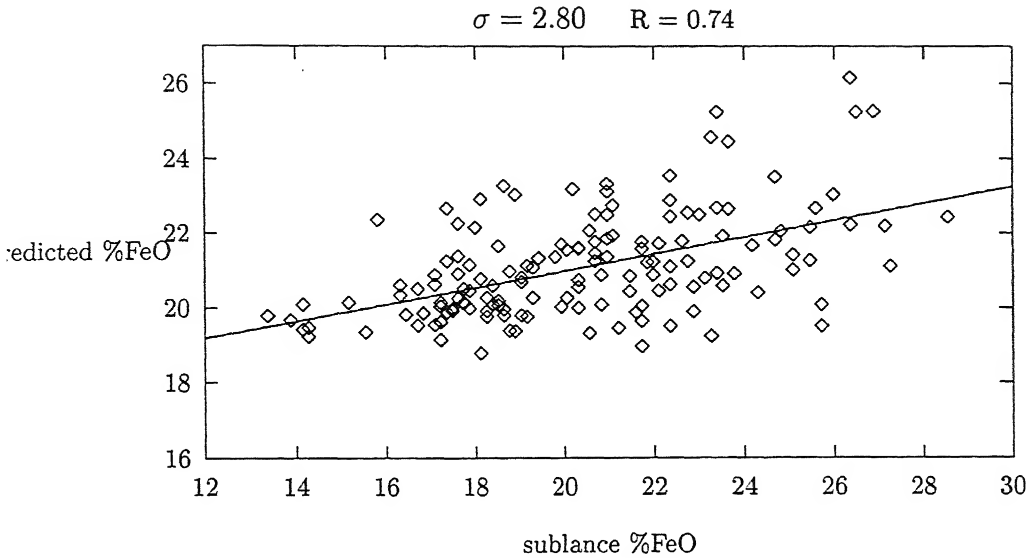

Figure 4.1: FeO content of slag (predicted by MLR) versus FeO content obtained by sublance model

When GAS was used for optimization then

$$\%FeO = 0.18 + 6.07\ exp\left(-1.29\ \log[\%C] - \frac{6514.2}{T}\right) + \frac{27067.5}{T} \tag{4.7}$$

$$\sigma = 2.73$$

$$R = 0.77$$

Fig(4.2) shows the plot of actual versus predicted FeO. It may be noted that actual FeO is the one predicted by dynamic control model. Since σ and R values for both the equations 4.6 and 4.7 are comparable, they yield almost same results.

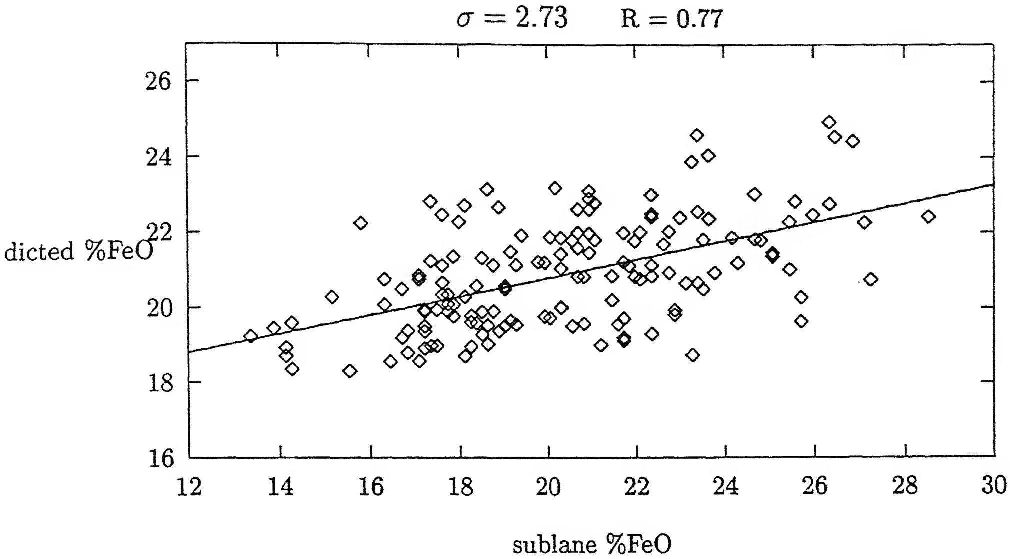

Figure 4.2: FeO content of slag (predicted by GAS) versus FeO content obtained by sublance model

In case of GAS typical GA parameters are: 100 generations, population size of 50, crossover probability (P_{cr}) = 0.8, mutation propability (P_m) = 0.001. The string length for each variable is 10 and hence for 5 variables the total string length is 50.

The variable range for the coefficients is

coefficient	minimum	maximum
C_1	-15.0	10.0
C_2	-15.0	10.0
C_3	-8000.0	8000.0
C_4	-15.0	10.0
C_5	-30000.0	30000.0

The input variables actual %FeO, %C , temparature, and predicted %FeO using regression and GAS are given in Table 4.1.

4.3 Optimization of Healy's equation by MLR and genetic adaptive search

Several interesting options are available for optimization of Healy's equation (2.32). For example, FeO predicted by dynamic model can be directly substituted into Healy's equation (2.32), or FeO can be predicted by equations 4.6 and 4.7, or additional terms like amount of ore added, return slag, and oxygen blown at second period etc., can be incorporated, or heats can be classified into two or more classes according to phosphorus content (low, high) and analyzed separately. Altogether seven options are dicussed below; in most cases both MLR and GAS have been used as optimization techniques to predict end point phosphorus in steel.

4.3.1 Option 1: Adjusting coefficients of Healy's Equation

The objective function for minimization is the sum of the residual squares.

$$\sum_{i=1}^{n}\left(log\left(\frac{(\%P)}{[\%P]}\right)_i - \left(C_1\left(\%CaO_i\right) + C_2\ log\left(\%Fe_{t_i}\right) + C_3 + \frac{C_4}{T_i}\right)\right)^2 \tag{4.8}$$

The plant data used for optimization are summarized in Table(4.3). When the coefficients C_1, C_2, C_3, and C_4 are optimized by MLR then the equation becomes,

$$log\left(\frac{(\%P)}{[\%P]}\right) = 4.44\left(\%CaO\right) - 0.03 log\left(\%Fe_t\right) + 0.64 + \frac{0.003}{T} \tag{4.9}$$

$$\sigma = 0.23$$

$$R = 0.76$$

Fig 4.3 shows the plot between actual and predicted %P in steel as obtained by regression (MLR).

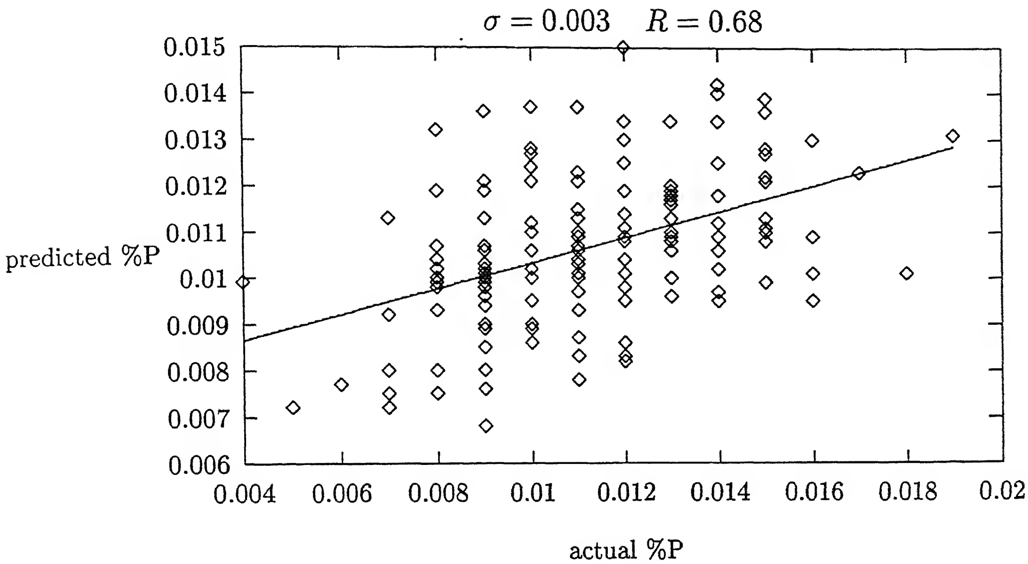

Figure 4.3: Phosphorus content of steel predicted by MLR (Eq.4.9) versus phophorus content of steel measured at end point

In the case of GAS various GA parameters are: generations = 100, population = 100, $P_{cr} = 0.8$, $P_m = 0.001$ and string length = 40

and the range of coefficients is,

coefficient	minimum	maximum
C_1	-10.0	10.0
C_2	-10.0	10.0
C_3	-50.0	50.0
C_4	-35000.0	35000.0

The optimized equation by GAS is

$$\log \frac{(\%P)}{[\%P]} = 0.05\,(\%CaO) + 2.79\ \log(\%Fe_t) - 16.73 + \frac{16806.9}{T} \tag{4.10}$$

$$\sigma = 0.36$$

$$R = 0.73$$

Fig 4.4 shows the plot between actual and predicted %P in steel by GAS

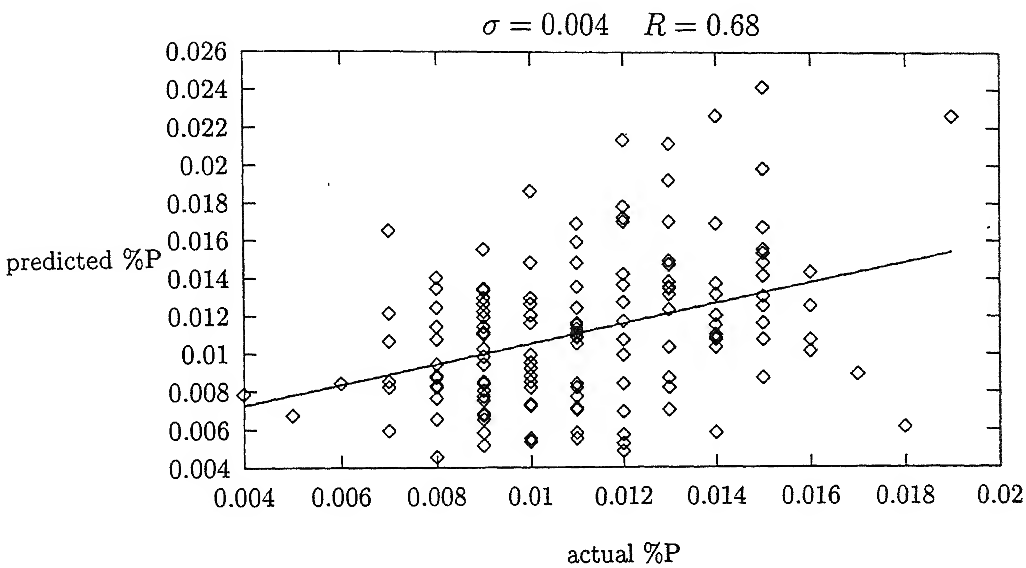

Figure 4.4: Phosphorus content of steel predicted by GAS (Eq. 4.10) versus phosphorus content of steel measured at end point

4.3.2 Option 2: Incorporation of additional parameters in Healy's Equation

From practical experience, it is well known that in addition to temparature, FeO and CaO content of slag, phosphorus in steel at end point is also affected by iron ore added and the amount of oxygen blown in the second blow period.

If these two additional parameters are included then the equation obtained by

regression is,

$$
\begin{aligned}
log\frac{(\%P)}{[\%P]} &= 0.03 - 0.03\,(\%CaO) + 0.79log\,(\%Fe_t) + 0.32 \times \frac{22350}{T} - 0.00012V_{O_2} \\
&\quad +0.236W_{ore} \qquad (4.11)
\end{aligned}
$$

$$
\begin{aligned}
\sigma &= 0.20 \\
\mathrm{R} &= 0.80
\end{aligned}
$$

Fig 4.5 shows the plot between actual and predicted %P in steel by regression

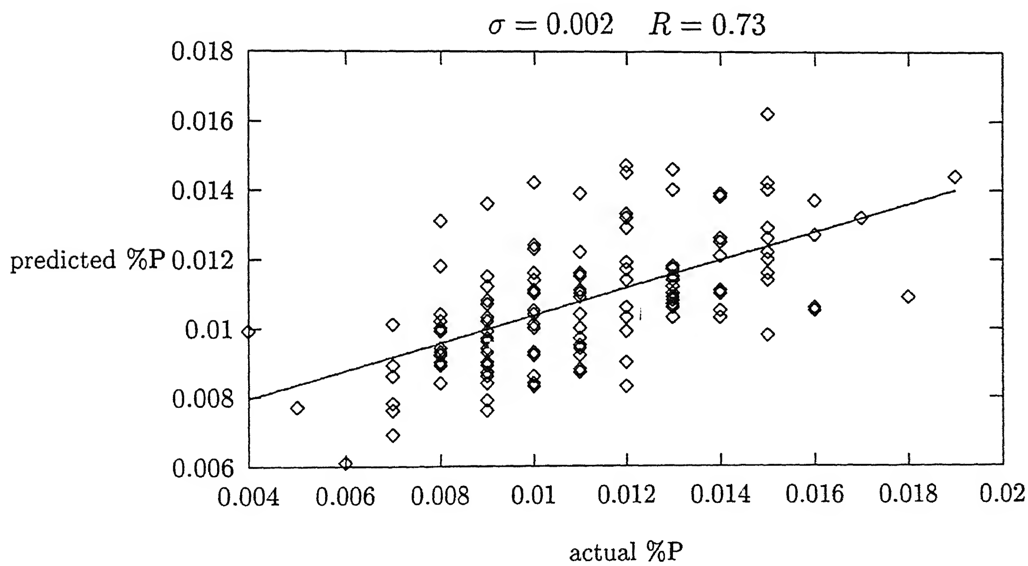

Figure 4.5: Phosphorus content of steel predicted by MLR (Eq. 4.11) versus phosphorus content of steel measured at end point

In the case of GAS various GA parameters are: generations = 100, population size = 100, $P_{cr} = 0.8$, $P_m = 0.001$ and string length = 60.

and the range of coefficients is

coefficient	minimum	maximum
C_1	-5.0	10.0
C_2	-5.0	10.0
C_3	-5.0	35.0
C_4	-30000.0	30000.0
C_5	-1.0	1.0
C_6	-1.0	1.0

Optimized equation by GAS is

$$\log\frac{(\%P)}{[\%P]} = -0.21\%CaO + 1.9log\,(\%Fe_t) + 12.9 + \frac{2023.46}{T} - 0.0001V_{O_2} -0.042W_{ore} \tag{4.12}$$

$$\sigma = 0.53$$

$$R = 0.78$$

Fig 4.6 shows the plot between actual and predicted %P in steel by GAS

4.3.3 Option 3: Use of Fe_t values predicted by regression

If the Fe_t value in Healy's equation (2.32) is replaced by regression predicted Fe_t value, then the optimized equation using regression is

$$log\frac{(\%P)}{[\%P]} = -0.05\%CaO + 0.15log\,(Fe_t) + 7.4 - \frac{0.005}{T} \tag{4.13}$$

$$\sigma = 0.23$$

$$R = 0.77$$

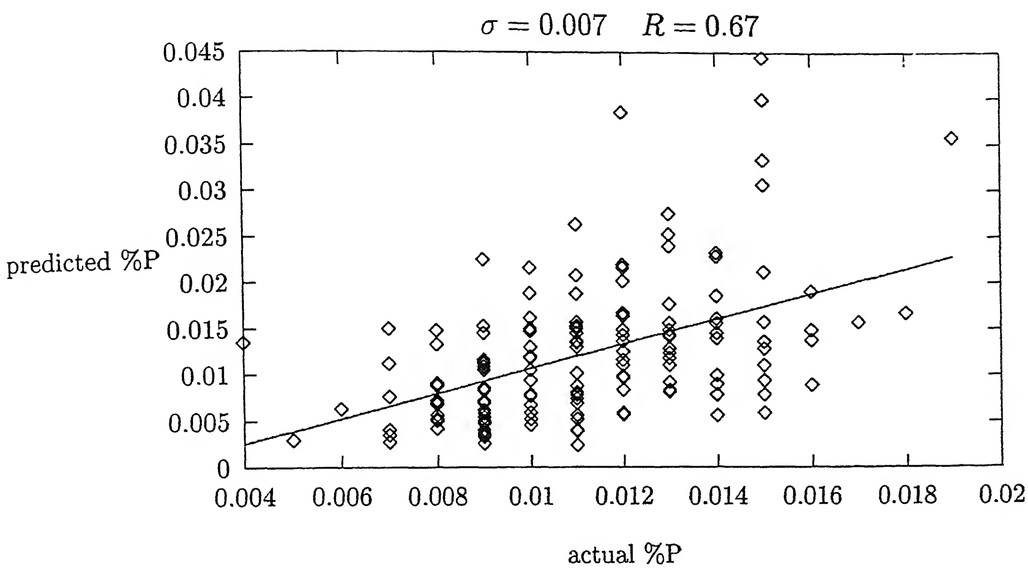

Figure 4.6: Phophorus content of steel predicted by GAS (Eq. 4.12) versus phosphorus content in steel measured at end point

Fig 4.7 shows the plot between actual and predicted %P in steel by regression

In GAS, various GA parameters are: generations = 100, population size = 100, $P_{cr} = 0.8$, $P_m = 0.001$ and string length = 50

variable range for coefficients is,

coefficient	minimum	maximum
C_1	-5.0	5.0
C_2	-5.0	10.0
C_3	-25.0	35.0
C_4	-30000.0	30000.0

Optimized equation by GAS is

$$log\frac{(\%P)}{[\%P]} = -0.03\%CaO + 0.78log(Fe_t) + 10.72 - \frac{10511.7}{T} \quad (4.14)$$

$$\sigma = 0.25$$

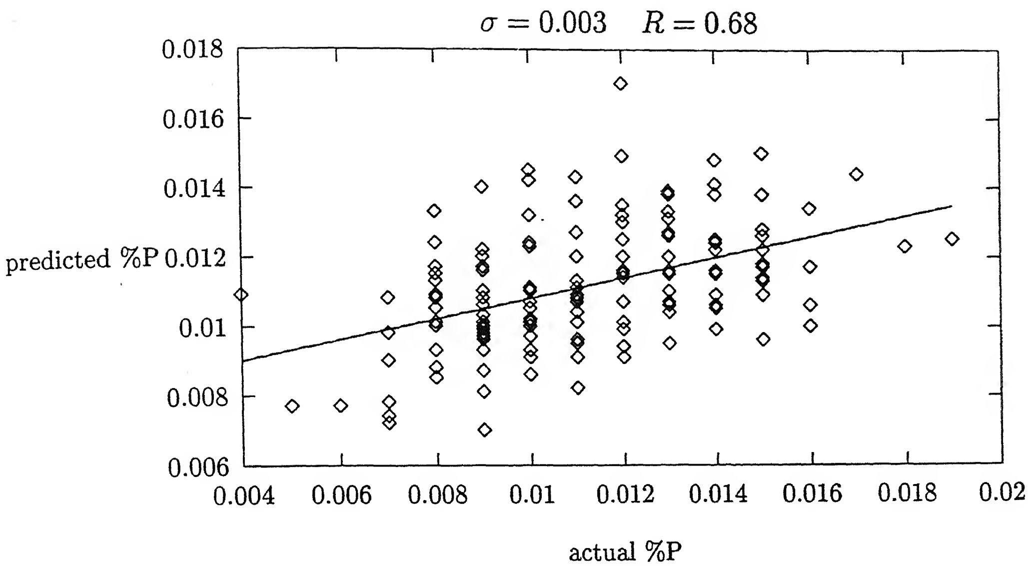

Figure 4.7: Phophorus content of steel predicted by MLR (Eq. 4.13) versus phosphorus content in steel measured at end point

$$R = 0.73$$

Fig 4.8 shows the plot between actual and predicted %P in steel by GAS

4.3.4 Option 4: Use of GAS predicted Fe_t values :-

The Fe_t values required in Healy's equation(2.32) are replaced with GA predicted Fe_t values using Eq.(4.7).

The regression optimized equation is,

$$\log \frac{(\%P)}{[\%P]} = -0.06\%CaO + 0.07log(Fe_t) + 7.71 - \frac{0.005}{T} \tag{4.15}$$

$$\sigma = 0.23$$

$$R = 0.76$$

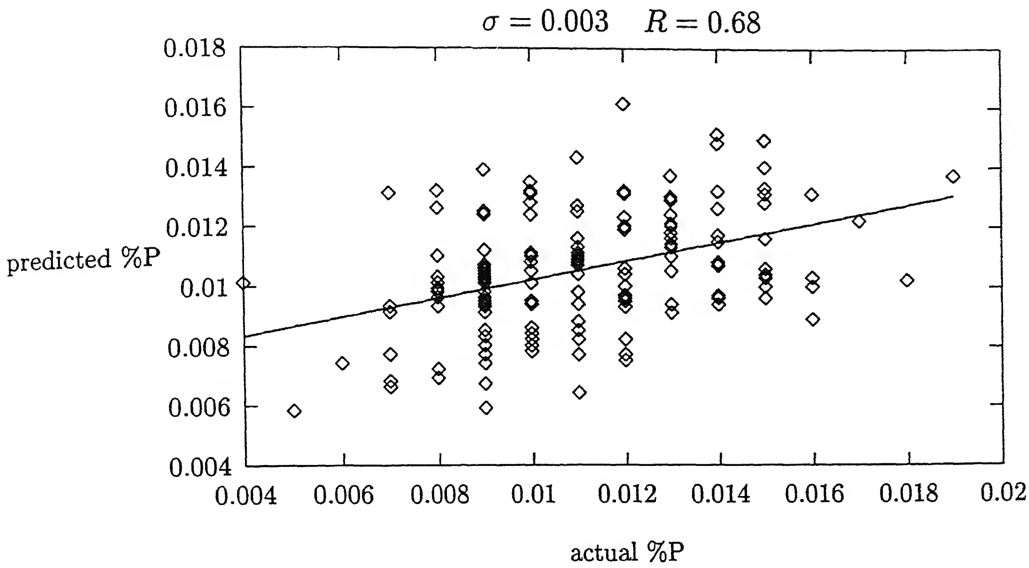

Figure 4.8: Phophorus content of steel predicted by GAS (Eq. 4.14) versus phosphorus content in steel measured at end point

Fig 4.9 shows the plot between actual and predicted %P in steel by regression

In case of GAS, various GA parameters are, generations = 100, population size = 100, $P_{cr} = 0.8$, $P_m = 0.001$, string length = 50

and variable range for coefficients

coefficient	minimum	maximum
C_1	-5.0	15.0
C_2	-5.0	15.0
C_3	-25.0	35.0
C_4	-30000.0	30000.0

Optimized equation by GAS is,

$$log\frac{(\%P)}{[\%P]} = 0.005\%CaO - 1.13log(Fe_t) + 11.4 - \frac{6853.1}{T} \tag{4.16}$$

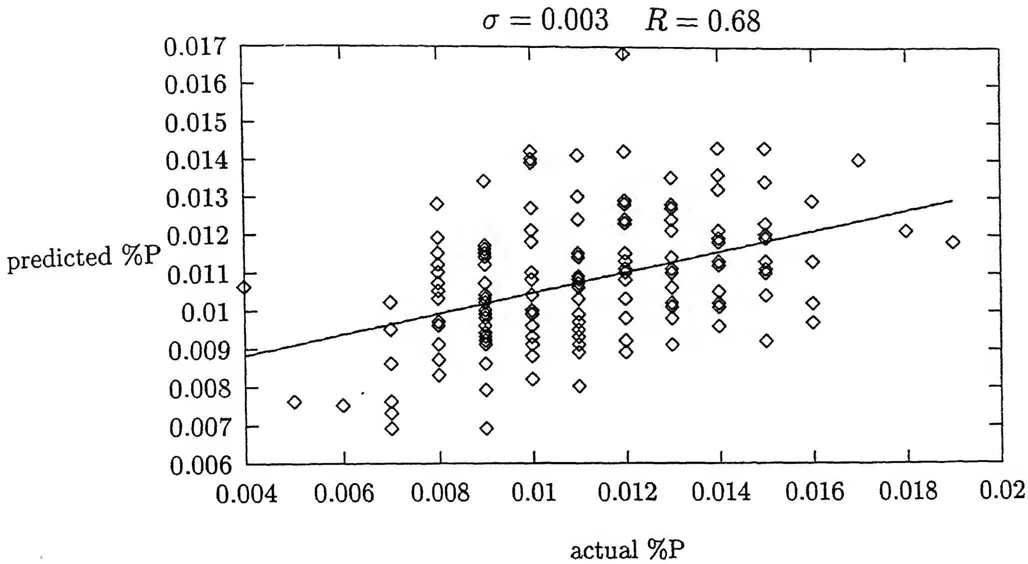

Figure 4.9: Phophorus content of steel predicted by MLR (Eq. 4.15) versus phosphorus content in steel measured at end point

$$\sigma = 0.23$$

$$R = 0.76$$

Fig 4.10 shows the plot between actual and predicted %P in steel by GAS

4.3.5 Option 5: Replacing Fe_t in Healy's equation with carbon and temparature at end point

The iron oxide content can be estimated through oxygen activity and temparature. The oxygen activity in turn depends on the end point carbon and temparature of the steel.

If the FeO obtained by Eq.(4.3) is substituted into Healy's equation (2.32) then

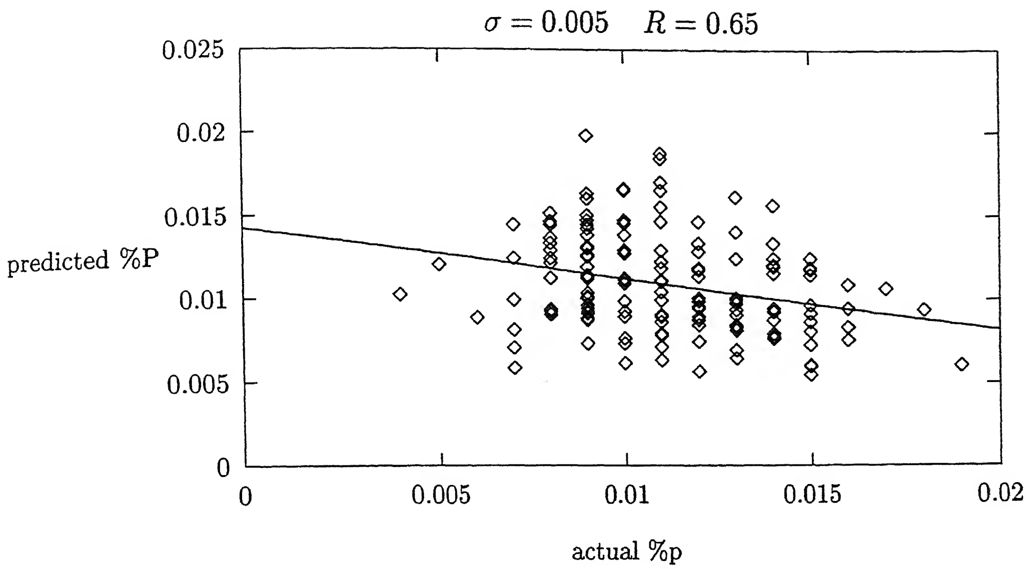

Figure 4.10: Phophorus content of steel predicted by GAS (Eq. 4.16) versus phosphorus content in steel measured at end point

the GAS predicted equation is

$$log\frac{(\%P)}{[\%P]} = 0.034\%CaO + 2.76log(Fe_t) + 0.7 - \frac{2100.2}{T} \tag{4.17}$$

$$Fe_t = \left(2.04\ exp\left[0.064log(\%C) - \frac{2567.7}{T}\right] + \frac{5910.4}{T}\right)/1.286 \tag{4.18}$$

$$\sigma = 0.42$$

$$\mathrm{R} = 0.76$$

Fig 4.11 shows the plot between actual and predicted %P in steel by GAS

Various GA parameters are: generations = 100, population size = 100, $P_{cr} = 0.85$, $P_m = 0.01$ and string length = 105

variable range for coefficients is,

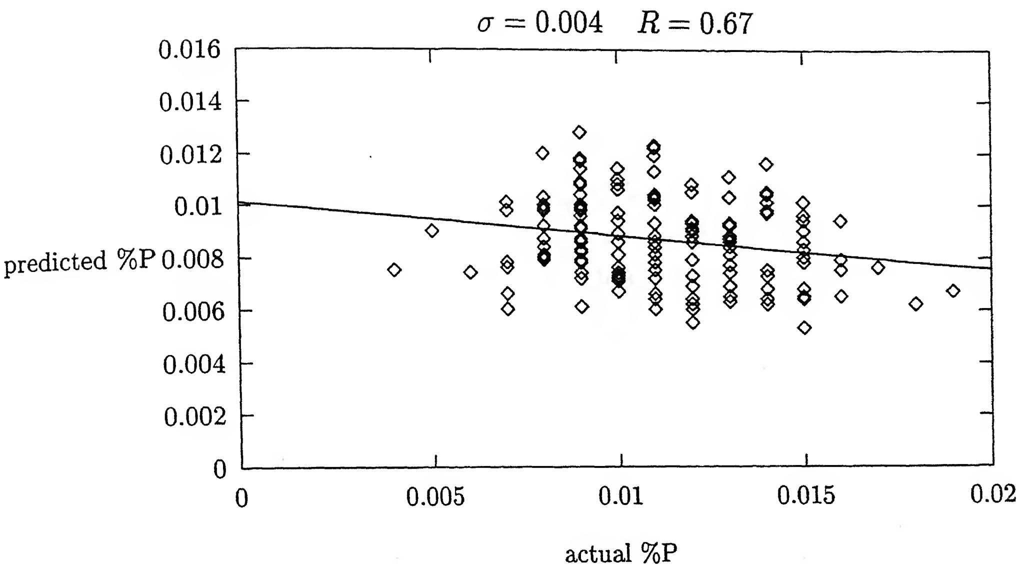

Figure 4.11: Phophorus content of steel predicted by GAS (Eq. 4.17) versus phosphorus content in steel measured at end point

coefficient	minimum	maximum
C_1	-5.0	5.0
C_2	-5.0	5.0
C_3	-5.0	5.0
C_4	-5.0	5.0
C_5	-8000.0	8000.0
C_6	-60000.0	60000.0
C_7	-15.0	50.0
C_8	-28000.0	28000.0

4.3.6 Option 6: Separate equations for two classes of heats

Operational data was devided into two classes : liquid steel with %P ≥ 0.01 and liquid steel with %P < 0.01. For the heats with %P ≥ 0.01 the regression equation is,

$$\log \frac{(\%P)}{[\%P]} = 3.79 - 0.022\%CaO + 0.7 \ \log(Fe_t) + \frac{0.00224}{T} \tag{4.19}$$

$$\sigma \quad = \quad 0.18$$

$$R = 0.73$$

Fig 4.12 shows the plot between actual and predicted %P in steel by regression

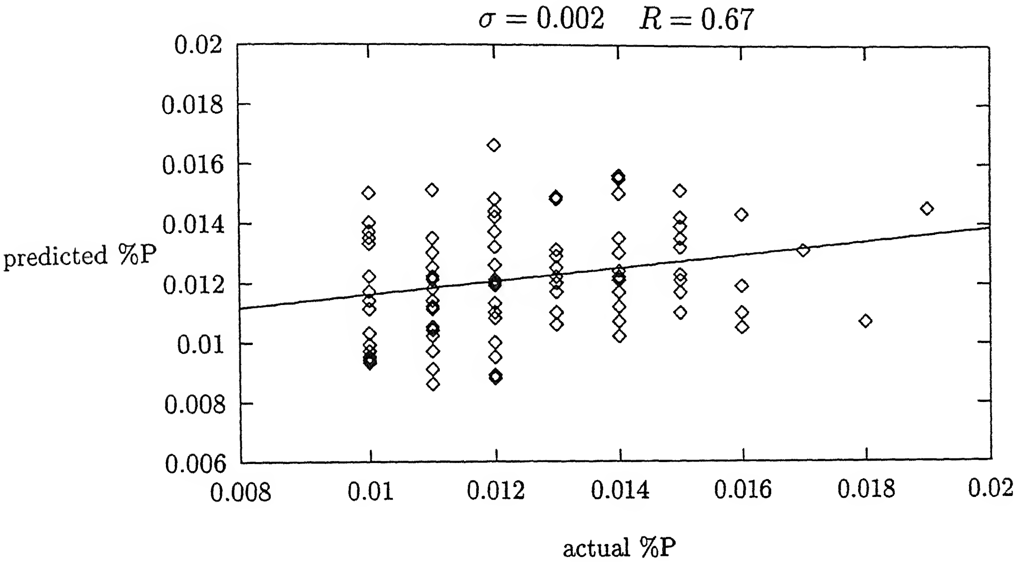

Figure 4.12: Phophorus content of steel predicted by MLR (Eq. 4.19) versus phosphorus content in steel measured at end point

In GAS various parameters are, generations = 100, population size = 100, P_{cr} = 0.8, P_m = 0.001 and string length = 50

Variable range for coefficients is,

coefficient	minimum	maximum
C_1	-10.0	10.0
C_2	-10.0	10.0
C_3	-50.0	50.0
C_4	-35000.0	35000.0

Optimized equation by GAS is

$$log\frac{(\%P)}{[\%P]} = 0.05\%CaO + 2.8log(Fe_t) - 16.4 + \frac{16738}{T} \tag{4.20}$$

$$\sigma = 0.36$$

$$R = 0.75$$

Fig 4.13 shows the plot between actual and predicted %P in steel by regression

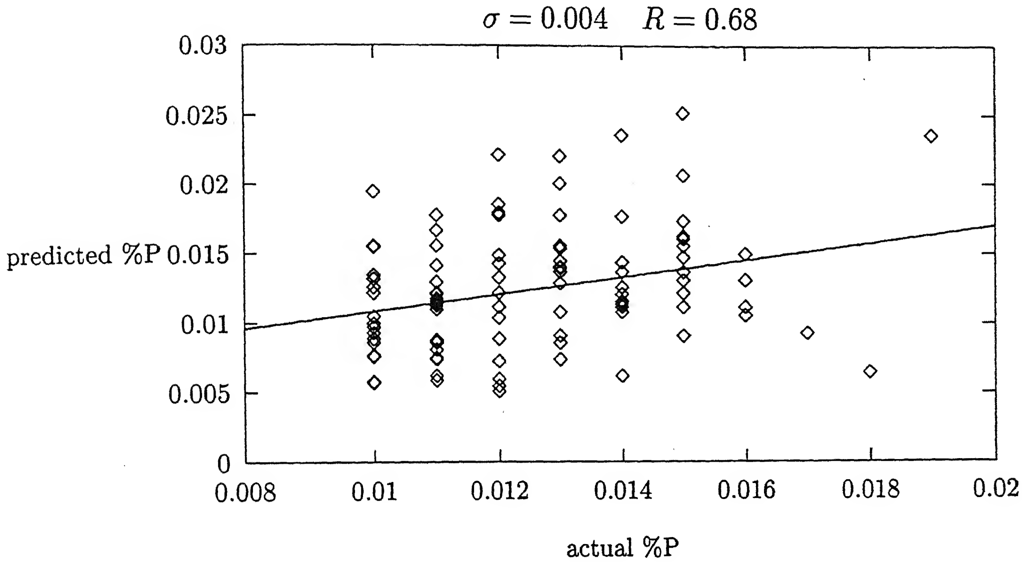

Figure 4.13: Phophorus content of steel predicted by MLR (Eq. 4.20) versus phosphorus content in steel measured at end point

4.3.7 Option 7: Replacing Fe_t with carbon

The equilibrium reaction at slag metal interface between FeO and carbon in steel can be written as,

$$FeO + C = Fe + CO \tag{4.21}$$

and, the equilibrium constant is given by

$$K = \frac{a_{Fe}\ p_{CO}}{a_{FeO}\ a_C} \tag{4.22}$$

since a_{Fe} =1, $p_{CO} \approx 1$, $a_{FeO}(a_{Fe_t})$ can be replaced in terms of %C itself. Hence, the Fe_t is estimated as

$$Fe_t = \frac{constant}{[\%C]}$$

In GAS, various parameters used for optimizing the equation are: generations = 100, population size = 100, $P_{cr} = 0.8$, $P_m = 0.01$and string length = 60

and variable range for coefficients is,

coefficient	minimum	maximum
C_1	-5.0	15.0
C_2	-5.0	15.0
C_3	0.0	15.0
C_4	-25.0	35.0
C_5	-25000.0	25000.0

GAS optimized equation for phosphorus prediction is

$$\log \frac{(\%P)}{[\%P]} = 0.005\%CaO + 0.32 \ \log\left(\frac{10.4}{[\%C]}\right) + 4.21 - \frac{2870.4}{T} \qquad (4.23)$$

$$\sigma = 0.27$$

$$\text{R} = 0.72$$

Fig 4.14 shows the plot between actual and predicted %P in steel by GAS. The input variables in all options including actual %P are shown in Table 4.3, and predicted %P for all options are given in Table 4.4.

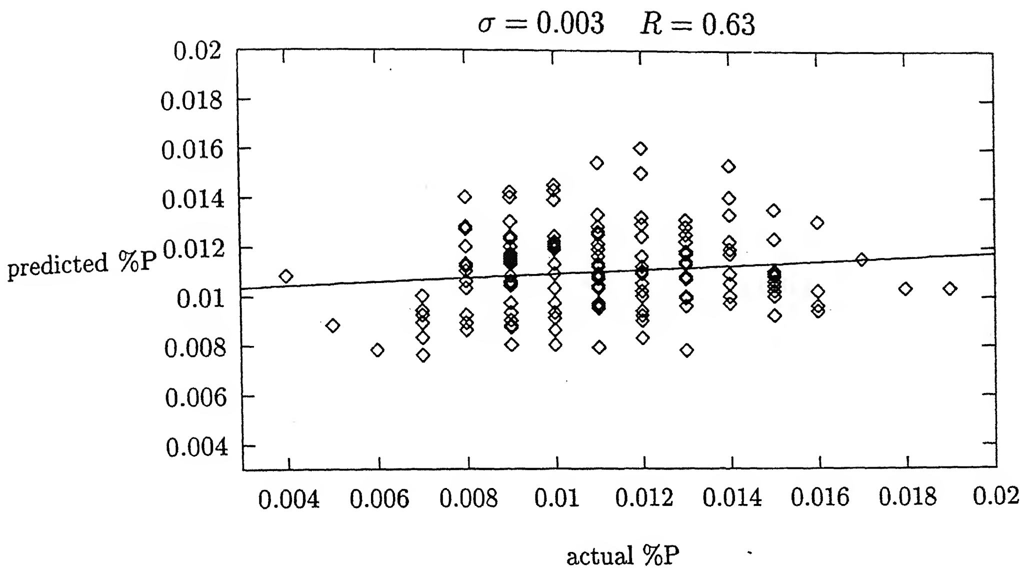

Figure 4.14: Phophorus content of steel predicted by MLR (Eq. 4.23) versus phosphorus content in steel measured at end point

4.4 Discussion

Accuracy of phosphorus prediction in steel at end point by using Healy's equation depends upon

- Reliability of operational data.
- Correct analysis /prediction of %CaO in slag and %FeO in slag.
- Errors in temperature measurement.
- Errors in analysis of steel (specially %C and %P).
- Error in estimation of weight of slag.
- Error in phosphorus analysis of charge materials.

In the present work operational data of only one campaign has been analyzed in which silicon content of hot metal was nearly constant (approximately 0.4 %). It is important to keep the silicon content constant because it affects the total amount of lime to be charged and hence overall slag volume at tap; it is practically found that phosphorus distribution improves with slag volume (provided basicity is kept constant). Lime quality also plays an important role. For example, the loss of ignition of lime (LOI) should be nearly constant if reproducible conditions are to be obtained.

The analysis of FeO content of slag poses several practical problems. Sometimes, depending upon lance height, the FeO content can abruptly increase without really affecting phosphorus distribution. This is due to inadequate slag-metal mixing and small time interval available for transfer of phosphorus from metal to slag or vice versa. Fig. 4.1 and 4.2 show the plots of actual versus predicted FeO. A slightly better prediction is obtained with GAS (rather than with MLR).

Temperature measurement at end point is usually within $\pm 4^oC$ but then waiting time, after the blow ends, has much greater influence on the measured temperature. Temperature falls at the rate of 1.5^oC per minute and hence waiting time before temperature measurement should be as less as possible. Errors in analysis of carbon and phophorus of steel are small and can be neglected.

Error in estimation of weight of slag mainly arises from errors in weighment of lime and also analysis of FeO content of final slag. The weight of slag directly affects the calculation of phophorus distribution. Additional error is introduced due to the

fact that phosphorus content of scrap ~~is~~ and ore are not analyzed and average phosphorus is assumed.

All these errors, as mentioned above, add up and ultimately decide the accuracy of phosphorus prediction.

Results of all the seven options of phosphorus prediction at end point are summarized in Table 4.2. Since only Option 1 (GAS) and Option 6 (GAS) correspond to the true form of Healy's equation (i.e positive coefficient for %CaO, positive coefficient for $\log Fe_t$ and also positive coefficient of (1/T)), it is recommended to use GAS Option 1 or GAS Option 6 in actual practice. It clearly shows that multiple linear regression, when applied to industrial data can lead to wrong estimation of coefficients inspite of the fact that it (MLR) can give a lower standard deviation and improved correlation coefficient (as in the case of Option 2 (MLR) in Table 4.2); wrong coefficients are obtained essentially due to error in data and stochasticity of oxygen steel making process itself.

According to Option 2 (Table 4.2), regression coefficient improves when volume of oxygen blown during second blow period and mass of iron ore added are incorporated. These two parameters can be incorporated in Option 1 (GAS) and Option 6 (GAS) to further improve the prediction by GAS but with a restriction that coefficients of %CaO, $\log \%Fe_t$ and temperature still remain positive. In the optimization procedure by GAS, it is possible to code the variables such that they do not become negative. This restriction can not be imposed in multiple linear regression and hence

Table 4.1: Predicted FeO content of slag by GAS and Regression on the basis of carbon and temparature at end point

Actual %FeO	%C	Temp	GAS %FeO	MLR %FeO
21.476	0.070	1661.0	20.186	20.415
25.463	0.060	1655.0	20.998	21.252
24.305	0.059	1702.0	21.169	20.381
18.518	0.075	1666.0	19.861	20.044
21.476	0.062	1666.0	20.818	20.830
20.833	0.062	1665.0	20.817	20.853
23.019	0.049	1665.0	22.373	22.483
18.390	0.065	1667.0	20.558	20.576
13.889	0.083	1670.0	19.429	19.641
16.461	0.114	1646.0	18.530	19.803
17.104	0.111	1656.0	18.546	19.524
16.847	0.104	1648.0	18.761	19.852
19.161	0.056	1682.0	21.470	21.118
17.490	0.097	1650.0	18.956	19.895
20.962	0.045	1668.0	23.080	23.309
16.847	0.085	1661.0	19.363	19.833
14.275	0.119	1664.0	18.328	19.201
14.146	0.100	1643.0	18.896	20.061
19.033	0.065	1658.0	20.559	20.792
18.390	0.081	1657.0	19.559	20.064
20.062	0.078	1654.0	19.718	20.249
25.463	0.050	1675.0	22.260	22.148
26.363	0.037	1660.0	24.917	26.134
26.492	0.039	1678.0	24.527	25.236
27.263	0.063	1651.0	20.726	21.103
21.733	0.058	1649.0	21.191	21.572
23.534	0.053	1661.0	21.790	21.907
25.977	0.048	1643.0	22.439	23.014
20.576	0.081	1685.0	19.493	19.305
24.691	0.053	1667.0	21.807	21.797
21.733	0.052	1678.0	21.978	21.760
20.705	0.052	1678.0	21.978	21.760
20.319	0.060	1679.0	21.023	20.729
20.962	0.052	1673.0	21.961	21.843
16.718	0.089	1669.0	19.170	19.503
23.277	0.041	1658.0	23.855	24.553
18.647	0.045	1674.0	23.116	23.246
26.877	0.039	1665.0	24.407	25.254
20.962	0.048	1679.0	22.600	22.485
23.662	0.041	1681.0	24.038	24.434

Actual %FeO	%C	Temp	GAS %FeO	MLR %FeO
17.361	0.047	1684.0	22.800	22.647
17.747	0.068	1678.0	20.319	20.112
16.332	0.072	1661.0	20.053	20.312
20.962	0.056	1670.0	21.443	21.347
18.133	0.101	1686.0	18.683	18.773
17.875	0.072	1656.0	20.060	20.443
20.062	0.053	1682.0	21.853	21.537
20.833	0.081	1657.0	19.559	20.064
20.319	0.056	1659.0	21.421	21.568
21.991	0.062	1665.0	20.817	20.853
18.647	0.095	1655.0	19.000	19.781
24.691	0.045	1653.0	22.995	23.485
18.904	0.084	1679.0	19.359	19.364
24.177	0.053	1675.0	21.831	21.656
22.762	0.061	1652.0	20.902	21.235
22.376	0.045	1650.0	22.979	23.523
22.634	0.054	1661.0	21.663	21.772
21.090	0.047	1677.0	22.763	22.729
21.090	0.053	1660.0	21.787	21.925
23.405	0.064	1656.0	20.641	20.910
22.762	0.051	1643.0	22.004	22.528
23.534	0.066	1664.0	20.478	20.579
23.148	0.064	1662.0	20.641	20.767
17.747	0.075	1664.0	19.864	20.096
23.405	0.039	1682.0	24.565	25.235
25.720	0.079	1681.0	19.607	19.485
25.720	0.069	1677.0	20.244	20.074
17.618	0.068	1673.0	20.320	20.232
23.277	0.102	1670.0	18.718	19.221
22.119	0.052	1682.0	21.992	21.695
20.319	0.073	1672.0	19.975	19.980
17.104	0.062	1676.0	20.825	20.607
20.962	0.046	1665.0	22.877	23.103
16.332	0.063	1673.0	20.731	20.590
17.232	0.074	1669.0	19.916	20.010
14.146	0.104	1663.0	18.691	19.399
22.891	0.077	1645.0	19.792	20.535
22.376	0.049	1669.0	22.390	22.423
18.776	0.074	1694.0	19.886	19.380
17.232	0.096	1677.0	18.881	19.122

Actual %FeO	%C	Temp	GAS %FeO	MLR %FeO
25.077	0.057	1682.0	21.353	20.995
22.376	0.062	1676.0	20.825	20.607
21.219	0.094	1667.0	18.988	19.449
19.933	0.077	1664.0	19.750	20.014
17.618	0.064	1657.0	20.641	20.886
21.605	0.081	1664.0	19.541	19.870
19.290	0.059	1668.0	21.111	21.060
17.232	0.085	1669.0	19.340	19.609
22.119	0.063	1680.0	20.735	20.434
21.733	0.091	1663.0	19.112	19.628
22.376	0.086	1672.0	19.287	19.497
16.718	0.066	1668.0	20.477	20.483
21.733	0.087	1691.0	19.190	18.950
25.591	0.047	1684.0	22.800	22.647
22.891	0.074	1674.0	19.909	19.881
20.705	0.055	1671.0	21.564	21.452
14.275	0.080	1681.0	19.553	19.447
17.361	0.097	1651.0	18.951	19.865
19.161	0.079	1671.0	19.627	19.750
18.518	0.089	1646.0	19.249	20.168
20.319	0.073	1651.0	20.006	20.530
26.363	0.048	1703.0	22.727	22.206
19.419	0.053	1696.0	21.902	21.312
18.261	0.077	1655.0	19.769	20.258
18.261	0.080	1664.0	19.591	19.904
18.647	0.082	1660.0	19.503	19.949
17.875	0.077	1666.0	19.746	19.961
15.561	0.123	1659.0	18.278	19.322
19.033	0.082	1666.0	19.487	19.782
23.405	0.048	1666.0	22.538	22.661
22.376	0.059	1667.0	21.110	21.081
20.190	0.045	1682.0	23.166	23.169
17.361	0.058	1665.0	21.211	21.225
15.175	0.069	1675.0	20.245	20.122
21.733	0.078	1662.0	19.700	20.030
19.033	0.066	1660.0	20.479	20.677
21.862	0.059	1662.0	21.104	21.189
19.804	0.058	1659.0	21.203	21.352
18.133	0.069	1650.0	20.266	20.752
18.518	0.057	1651.0	21.298	21.628
17.618	0.059	1654.0	21.095	21.365

Actual %FeO	%C	Temp	GAS %FeO	MLR %FeO
19.933	0.058	1644.0	21.186	21.684
19.290	0.082	1649.0	19.533	20.259
20.705	0.048	1678.0	22.595	22.498
17.747	0.072	1654.0	20.063	20.496
18.261	0.097	1655.0	18.934	19.745
27.135	0.050	1673.0	22.252	22.179
20.319	0.053	1678.0	21.840	21.604
17.490	0.074	1671.0	19.913	19.958
20.705	0.062	1649.0	20.812	21.227
21.991	0.054	1692.0	21.751	21.219
15.818	0.050	1663.0	22.212	22.336
18.904	0.047	1655.0	22.653	23.020
22.376	0.048	1652.0	22.476	22.869
23.662	0.049	1656.0	22.336	22.623
18.776	0.059	1673.0	21.118	20.954
13.374	0.089	1660.0	19.200	19.759
17.232	0.075	1663.0	19.866	20.123
17.232	0.082	1673.0	19.470	19.591
17.104	0.063	1661.0	20.727	20.866
18.133	0.047	1663.0	22.691	22.908
20.576	0.053	1653.0	21.769	22.058
23.791	0.061	1667.0	20.912	20.894
28.549	0.049	1670.0	22.394	22.408
25.077	0.056	1667.0	21.437	21.406
18.004	0.050	1675.0	22.260	22.148
17.618	0.049	1682.0	22.448	22.239
17.875	0.057	1675.0	21.338	21.131
24.820	0.053	1654.0	21.771	22.039

Table 4.2: Summarized Results

Option	Method	Equation	for $\log\frac{(\%p)}{[\%p]}$		for %P	
			σ	R	σ	R
1	MLR	$log\left(\frac{(\%p)}{[\%p]}\right) = 4.44\,(\%CaO) - 0.03log\,(\%Fe_t) + 0.64 + \frac{0.003}{T}$	0.23	0.76	0.003	0.68
	GAS	$\log\frac{(\%p)}{[\%p]} = 0.05\,(\%CaO) + 2.79\ \log\,(\%Fe_t) - 16.73 + \frac{16806.9}{T}$	0.36	0.73	0.004	0.68
2	MLR	$log\frac{(\%P)}{[\%P]} = 0.03 - 0.03\,(\%CaO) + 0.79log\,(\%Fe_t) + 0.32 \times \frac{22350}{T} - 0.00012V_{O_2} + 0.236\ W_{ore}$	0.20	0.80	0.002	0.73
	GAS	$\log\frac{(\%P)}{[\%P]} = -0.21\%CaO + 1.9log\,(\%Fe_t) + 12.9 + \frac{2023.46}{T} - 0.0001V_{O_2} - 0.042W_{ore}$	0.53	0.78	0.007	0.67
3	MLR	$log\frac{(\%p)}{[\%p]} = -0.05\%CaO + 0.15log\,(Fe_t) + 7.4 - \frac{0.005}{T}$	0.23	0.77	0.003	0.68
	GAS	$log\frac{(\%p)}{[\%p]} = -0.03\%CaO + 0.78log(Fe_t) + 10.72 - \frac{10511.7}{T}$	0.25	0.73	0.003	0.68
4	MLR	$\log\frac{(\%p)}{[\%p]} = -0.06\%CaO + 0.07log(Fe_t) + 7.71 - \frac{0.005}{T}$	0.23	0.76	0.003	0.68
	GAS	$log\frac{(\%p)}{[\%p]} = 0.005\%CaO - 1.13log(Fe_t) + 11.4 - \frac{6853.1}{T}$	0.23	0.76	0.005	0.65
5	GAS	$log\frac{(\%p)}{[\%p]} = 0.034\%CaO + 2.76log(Fe_t) + 0.7 - \frac{2100.2}{T}$	0.42	0.76	0.004	0.67
6	MLR	$\log\frac{(\%p)}{[\%p]} = 3.79 - 0.022\%CaO + 0.7\ \log(Fe_t) + \frac{0.00224}{T}$	0.18	0.73	0.002	0.67
	GAS	$log\frac{(\%p)}{[\%p]} = 0.05\%CaO + 2.8log(Fe_t) - 16.4 + \frac{16738}{T}$	0.36	0.75	0.004	0.68
7	GAS	$\log\frac{(\%p)}{[\%p]} = 0.005\%CaO + 0.32\ \log\left(\frac{10.4}{[\%C]}\right) + 4.21 - \frac{2870.4}{T}$	0.27	0.72	0.003	0.63

Table 4.3: Various inputs used for optimizing Healy's equation

P actual%	CaO %	Fe_t %	T K	C %	V_{O_2} Nm^3	W_{ore} Tons
0.013	65.4	16.70	1661.0	0.070	1700.0	4.644
0.010	62.8	19.80	1655.0	0.060	1390.0	4.084
0.011	59.6	18.90	1702.0	0.059	2000.0	2.012
0.016	63.8	14.40	1666.0	0.075	1980.0	3.200
0.012	60.9	16.70	1666.0	0.062	2300.0	3.634
0.012	62.6	16.20	1665.0	0.062	1950.0	1.508
0.010	60.3	17.90	1665.0	0.049	2300.0	5.302
0.013	62.8	14.30	1667.0	0.065	1990.0	3.678
0.019	66.3	10.80	1670.0	0.083	1790.0	3.000
0.011	67.2	12.80	1646.0	0.114	1160.0	7.670
0.012	67.1	13.30	1656.0	0.111	1280.0	3.580
0.011	66.3	13.10	1648.0	0.104	1610.0	3.930
0.012	61.7	14.90	1682.0	0.056	1980.0	4.170
0.010	66.3	13.60	1650.0	0.097	1440.0	4.868
0.006	60.6	16.30	1668.0	0.045	1680.0	13.000
0.013	64.6	13.10	1661.0	0.085	1300.0	5.458
0.015	69.1	11.10	1664.0	0.119	1610.0	3.704
0.007	65.8	11.00	1643.0	0.100	1100.0	4.918
0.010	62.8	14.80	1658.0	0.065	1990.0	3.510
0.009	63.6	14.30	1657.0	0.081	1550.0	3.704
0.015	64.2	15.60	1654.0	0.078	1870.0	2.584
0.011	61.5	19.80	1675.0	0.050	2380.0	1.820
0.011	57.4	20.50	1660.0	0.037	2340.0	4.018
0.009	57.2	20.60	1678.0	0.039	2590.0	5.574
0.009	57.4	21.20	1651.0	0.063	2100.0	4.374
0.010	60.0	16.90	1649.0	0.058	2160.0	3.728
0.013	62.0	18.30	1661.0	0.053	1880.0	2.662
0.011	57.5	20.20	1643.0	0.048	2560.0	3.610
0.012	64.3	16.00	1685.0	0.081	2000.0	1.952
0.009	62.9	19.20	1667.0	0.053	2280.0	0.000
0.014	60.9	16.90	1678.0	0.052	1780.0	1.000
0.015	62.1	16.10	1678.0	0.052	1780.0	1.000
0.016	62.7	15.80	1679.0	0.060	1900.0	1.260
0.010	62.4	16.30	1673.0	0.052	1680.0	1.004
0.015	66.3	13.00	1669.0	0.089	1780.0	0.000
0.007	57.7	18.10	1658.0	0.041	1860.0	2.570
0.008	62.0	14.50	1674.0	0.045	1490.0	3.610
0.007	57.1	20.90	1665.0	0.039	2400.0	5.940
0.011	60.6	16.30	1679.0	0.048	1700.0	2.312
0.008	60.2	18.40	1681.0	0.041	1880.0	2.732
0.013	63.5	13.50	1684.0	0.047	1960.0	3.132
0.015	62.8	13.80	1678.0	0.068	1780.0	1.466
0.013	61.7	12.70	1661.0	0.072	1580.0	2.700

P actual%	CaO %	Fe_t %	T K	C %	V_{O_2} Nm^3	W_{ore} Tons
0.014	61.6	16.30	1670.0	0.056	1890.0	0.000
0.014	66.4	14.10	1686.0	0.101	1800.0	3.792
0.008	64.8	13.90	1656.0	0.072	1600.0	2.972
0.009	62.9	15.60	1682.0	0.053	1900.0	3.902
0.004	64.2	16.20	1657.0	0.081	1980.0	3.612
0.008	61.1	15.80	1659.0	0.056	1800.0	3.112
0.010	63.3	17.10	1665.0	0.062	1800.0	3.702
0.013	68.2	14.50	1655.0	0.095	1520.0	2.990
0.008	61.4	19.20	1653.0	0.045	1820.0	3.432
0.010	64.5	14.70	1679.0	0.084	1580.0	3.110
0.011	64.2	18.80	1675.0	0.053	1500.0	1.680
0.010	62.5	17.70	1652.0	0.061	1500.0	1.308
0.011	60.6	17.40	1650.0	0.045	1800.0	3.782
0.014	60.9	17.60	1661.0	0.054	2180.0	1.308
0.012	61.0	16.40	1677.0	0.047	1930.0	3.424
0.009	61.2	16.40	1660.0	0.053	1800.0	6.412
0.010	63.5	18.20	1656.0	0.064	1960.0	3.714
0.011	60.5	17.70	1643.0	0.051	1990.0	6.200
0.008	61.7	18.30	1664.0	0.066	1480.0	4.002
0.008	60.8	18.00	1662.0	0.064	1680.0	4.498
0.009	64.4	13.80	1664.0	0.075	1860.0	4.902
0.012	60.1	18.20	1682.0	0.039	2100.0	4.198
0.010	63.0	20.00	1681.0	0.079	1640.0	3.018
0.009	60.8	20.00	1677.0	0.069	1700.0	3.822
0.012	63.9	13.70	1673.0	0.068	1800.0	1.524
0.012	67.6	18.10	1670.0	0.102	1610.0	3.188
0.015	64.2	17.20	1682.0	0.052	1020.0	5.248
0.017	67.2	15.80	1672.0	0.073	1480.0	0.000
0.013	62.1	13.30	1676.0	0.062	1650.0	3.114
0.007	62.7	16.30	1665.0	0.046	1700.0	4.420
0.014	62.3	12.70	1673.0	0.063	1940.0	4.990
0.014	64.0	13.40	1669.0	0.074	1700.0	4.968
0.015	66.1	11.00	1663.0	0.104	1600.0	7.244
0.009	64.6	17.80	1645.0	0.077	1860.0	3.174

P actual%	CaO %	Fe_t %	T K	C %	V_{O_2} Nm^3	W_{ore} Tons
0.008	61.8	17.40	1669.0	0.049	1680.0	4.148
0.016	65.1	14.60	1694.0	0.074	1700.0	0.624
0.014	68.6	13.40	1677.0	0.096	1380.0	0.000
0.012	63.9	19.50	1682.0	0.057	1700.0	0.000
0.012	69.5	17.40	1676.0	0.062	1780.0	0.000
0.012	69.5	17.40	1676.0	0.062	1780.0	0.000
0.018	67.8	16.50	1667.0	0.094	1680.0	0.000
0.011	63.2	15.50	1664.0	0.077	2050.0	1.888
0.013	64.2	13.70	1657.0	0.064	2200.0	8.052
0.014	67.0	16.80	1664.0	0.081	1740.0	0.000
0.009	62.3	15.00	1668.0	0.059	1960.0	3.024
0.012	63.8	13.40	1669.0	0.085	1930.0	5.218
0.010	64.1	17.20	1680.0	0.063	2120.0	1.300
0.012	65.1	16.90	1663.0	0.091	1760.0	2.352
0.008	62.5	17.40	1672.0	0.086	1900.0	3.992
0.011	62.4	13.00	1668.0	0.066	1700.0	8.428
0.011	64.5	16.90	1691.0	0.087	1580.0	2.068
0.009	57.6	19.90	1684.0	0.047	2170.0	1.198
0.010	61.8	17.80	1674.0	0.074	1980.0	5.878
0.009	59.8	16.10	1671.0	0.055	1960.0	6.492
0.012	66.0	11.10	1681.0	0.080	1950.0	5.360
0.012	63.5	13.50	1651.0	0.097	1480.0	2.902
0.009	63.2	14.90	1671.0	0.079	1800.0	3.082
0.009	62.1	14.40	1646.0	0.089	2170.0	6.180
0.011	60.9	15.80	1651.0	0.073	2140.0	3.810
0.005	58.9	20.50	1703.0	0.048	1950.0	3.392
0.012	63.2	15.10	1696.0	0.053	1840.0	3.908
0.011	64.1	14.20	1655.0	0.077	1880.0	0.954
0.009	65.3	14.20	1664.0	0.080	1740.0	4.620
0.012	64.7	14.50	1660.0	0.082	1780.0	4.708
0.016	65.4	13.90	1666.0	0.077	1680.0	2.630
0.013	65.0	12.10	1659.0	0.123	1680.0	3.050
0.014	62.9	14.80	1666.0	0.082	1880.0	1.510
0.009	59.4	18.20	1666.0	0.048	1980.0	4.024
0.009	60.4	17.40	1667.0	0.059	1760.0	4.624
0.007	59.4	15.70	1682.0	0.045	1760.0	4.522
0.007	63.2	13.50	1665.0	0.058	1660.0	6.868
0.010	64.5	11.80	1675.0	0.069	1820.0	4.752

P actual %	CaO %	Fe_t %	T K	C %	V_{O_2} Nm^3	W_{ore} Tons
0.009	64.3	16.90	1662.0	0.078	1880.0	1.730
0.008	62.1	14.80	1660.0	0.066	2060.0	7.048
0.009	60.5	17.00	1662.0	0.059	2060.0	3.088
0.011	61.9	15.40	1659.0	0.058	2360.0	3.310
0.013	62.9	14.10	1650.0	0.069	1970.0	3.410
0.011	62.7	14.40	1651.0	0.057	2080.0	5.888
0.011	62.8	13.70	1654.0	0.059	2040.0	4.000
0.014	61.2	15.50	1644.0	0.058	1920.0	1.210
0.014	63.6	15.00	1649.0	0.082	1780.0	3.150
0.015	61.4	16.10	1678.0	0.048	2350.0	3.608
0.014	62.9	13.80	1654.0	0.072	1800.0	4.110
0.011	62.6	14.20	1655.0	0.097	2370.0	5.312
0.008	61.7	21.10	1673.0	0.050	2760.0	0.000
0.013	63.1	15.80	1678.0	0.053	1760.0	0.000
0.015	63.7	13.60	1671.0	0.074	1640.0	0.730
0.009	60.1	16.10	1649.0	0.062	1720.0	3.102
0.009	61.6	17.10	1692.0	0.054	1660.0	3.560
0.011	64.1	12.30	1663.0	0.050	1600.0	6.008
0.010	61.5	14.70	1655.0	0.047	2000.0	7.714
0.008	59.4	17.40	1652.0	0.048	2300.0	5.020
0.009	59.0	18.40	1656.0	0.049	1660.0	6.118
0.009	62.2	14.60	1673.0	0.059	1820.0	4.302
0.015	66.3	10.40	1660.0	0.089	1780.0	4.218
0.013	63.7	13.40	1663.0	0.075	2180.0	2.822
0.015	66.8	13.40	1673.0	0.082	1970.0	0.290
0.013	64.6	13.30	1661.0	0.063	1380.0	4.242
0.009	62.0	14.10	1663.0	0.047	1480.0	2.898
0.008	61.1	16.00	1653.0	0.053	1420.0	3.002
0.013	63.9	18.50	1667.0	0.061	1890.0	3.950
0.011	60.1	22.20	1670.0	0.049	1500.0	0.000
0.009	58.5	19.50	1667.0	0.056	2490.0	1.020
0.010	62.0	14.00	1675.0	0.050	2390.0	3.440
0.010	62.6	13.70	1682.0	0.049	2190.0	3.968
0.015	62.2	13.90	1675.0	0.057	1900.0	0.150
0.009	58.9	19.30	1654.0	0.053	1900.0	1.004

4.4: Predicted %P in steel at end point by using MLR and GAS; seven options considerd

opt1 GAS	opt2 MLR	opt2 GAS	opt3 MLR	opt3 GAS	opt4 MLR	opt4 GAS	opt5 GAS	opt7 GAS	opt6 MLR	opt6 GAS
0.0082	0.0114	0.0155	0.0138	0.0121	0.0135	0.0121	0.0086	0.0122	0.0129	0.0085
0.0053	0.0084	0.0045	0.0111	0.0095	0.0110	0.0095	0.0089	0.0113	0.0103	0.0056
0.0082	0.0088	0.0038	0.0082	0.0064	0.0080	0.0064	0.0088	0.0095	0.0086	0.0085
0.0143	0.0137	0.0190	0.0134	0.0131	0.0129	0.0131	0.0094	0.0130	0.0143	0.0149
0.0099	0.0103	0.0098	0.0101	0.0095	0.0098	0.0095	0.0094	0.0112	0.0108	0.0103
0.0117	0.0133	0.0115	0.0132	0.0123	0.0128	0.0123	0.0105	0.0132	0.0137	0.0121
0.0095	0.0105	0.0093	0.0110	0.0101	0.0108	0.0101	0.0110	0.0119	0.0117	0.0099
0.0134	0.0115	0.0141	0.0110	0.0110	0.0106	0.0110	0.0084	0.0108	0.0122	0.0139
0.0226	0.0144	0.0357	0.0125	0.0137	0.0118	0.0137	0.0067	0.0103	0.0145	0.0235
0.0109	0.0094	0.0187	0.0120	0.0127	0.0114	0.0127	0.0060	0.0109	0.0122	0.0113
0.0107	0.0106	0.0163	0.0120	0.0120	0.0115	0.0120	0.0062	0.0109	0.0121	0.0111
0.0115	0.0110	0.0207	0.0120	0.0127	0.0115	0.0127	0.0066	0.0112	0.0125	0.0120
0.0142	0.0114	0.0110	0.0107	0.0100	0.0103	0.0100	0.0091	0.0105	0.0119	0.0148
0.0116	0.0114	0.0188	0.0132	0.0135	0.0127	0.0135	0.0073	0.0121	0.0135	0.0121
0.0084	0.0061	0.0062	0.0077	0.0074	0.0075	0.0074	0.0074	0.0078	0.0131	0.0153
0.0147	0.0110	0.0128	0.0120	0.0124	0.0114	0.0124	0.0077	0.0114	0.0132	0.0160
0.0153	0.0126	0.0444	0.0126	0.0131	0.0119	0.0131	0.0053	0.0100	0.0133	0.0134
0.0165	0.0101	0.0149	0.0108	0.0131	0.0102	0.0131	0.0060	0.0100	0.0139	0.0111
0.0129	0.0123	0.0146	0.0123	0.0124	0.0118	0.0124	0.0094	0.0122	0.0091	0.0061
0.0129	0.0115	0.0112	0.0122	0.0124	0.0117	0.0124	0.0086	0.0124	0.0097	0.0074
0.0107	0.0129	0.0157	0.0138	0.0133	0.0134	0.0133	0.0094	0.0135	0.0117	0.0104
0.0058	0.0092	0.0077	0.0095	0.0077	0.0093	0.0077	0.0086	0.0096	0.0129	0.0090
0.0071	0.0087	0.0039	0.0091	0.0082	0.0089	0.0082	0.0119	0.0108	0.0104	0.0073
0.0077	0.0087	0.0049	0.0087	0.0074	0.0086	0.0074	0.0118	0.0106	0.0113	0.0103
0.0067	0.0087	0.0032	0.0099	0.0091	0.0098	0.0091	0.0128	0.0142	0.0112	0.0111
0.0099	0.0104	0.0078	0.0107	0.0108	0.0104	0.0108	0.0106	0.0124	0.0121	0.0121
0.0087	0.0118	0.0083	0.0131	0.0116	0.0128	0.0116	0.0111	0.0131	0.0105	0.0105
0.0070	0.0092	0.0051	0.0096	0.0094	0.0095	0.0094	0.0123	0.0126	0.0095	0.0088
0.0099	0.0117	0.0142	0.0114	0.0096	0.0111	0.0096	0.0079	0.0110	0.0123	0.0136
0.0051	0.0090	0.0082	0.0093	0.0077	0.0092	0.0077	0.0074	0.0088	0.0118	0.0129
0.0107	0.0110	0.0055	0.0105	0.0094	0.0102	0.0094	0.0098	0.0109	0.0106	0.0144
0.0116	0.0120	0.0078	0.0114	0.0103	0.0111	0.0103	0.0096	0.0109	0.0123	0.0162
0.0101	0.0106	0.0088	0.0100	0.0089	0.0097	0.0089	0.0079	0.0096	0.0131	0.0200
0.0085	0.0092	0.0058	0.0091	0.0082	0.0088	0.0082	0.0074	0.0086	0.0124	0.0120
0.0130	0.0129	0.0211	0.0118	0.0116	0.0113	0.0116	0.0065	0.0102	0.0122	0.0125
0.0082	0.0078	0.0026	0.0078	0.0077	0.0076	0.0077	0.0098	0.0094	0.0122	0.0092
0.0134	0.0102	0.0068	0.0101	0.0099	0.0097	0.0099	0.0084	0.0092	0.0129	0.0090
0.0059	0.0069	0.0034	0.0074	0.0066	0.0073	0.0066	0.0101	0.0092	0.0150	0.0155
0.0124	0.0111	0.0055	0.0107	0.0098	0.0103	0.0098	0.0103	0.0109	0.0130	0.0080
0.0076	0.0084	0.0041	0.0085	0.0072	0.0083	0.0072	0.0087	0.0086	0.0140	0.0096
0.0138	0.0106	0.0143	0.0095	0.0091	0.0091	0.0091	0.0069	0.0078	0.0135	0.0109

opt1 MLR	opt1 GAS	opt2 MLR	opt2 GAS	opt3 MLR	opt3 GAS	opt4 MLR	opt4 GAS	opt5 GAS	opt7 GAS	opt6 MLR
0.0110	0.0155	0.0122	0.0110	0.0109	0.0106	0.0104	0.0106	0.0083	0.0106	0.0130
0.0116	0.0192	0.0118	0.0091	0.0107	0.0120	0.0101	0.0120	0.0088	0.0114	0.0126
0.0112	0.0115	0.0125	0.0077	0.0116	0.0108	0.0113	0.0108	0.0101	0.0119	0.0137
0.0112	0.0120	0.0121	0.0232	0.0122	0.0107	0.0118	0.0107	0.0068	0.0109	0.0114
0.0119	0.0124	0.0118	0.0147	0.0124	0.0126	0.0119	0.0126	0.0079	0.0112	0.0095
0.0102	0.0111	0.0107	0.0111	0.0106	0.0095	0.0103	0.0095	0.0083	0.0097	0.0093
0.0099	0.0078	0.0099	0.0134	0.0109	0.0101	0.0106	0.0101	0.0075	0.0108	0.0148
0.0132	0.0140	0.0131	0.0089	0.0133	0.0132	0.0128	0.0132	0.0120	0.0140	0.0142
0.0112	0.0088	0.0111	0.0104	0.0124	0.0111	0.0121	0.0111	0.0094	0.0120	0.0117
0.0120	0.0087	0.0118	0.0239	0.0139	0.0129	0.0135	0.0129	0.0065	0.0113	0.0131
0.0098	0.0065	0.0092	0.0055	0.0109	0.0098	0.0107	0.0098	0.0099	0.0110	0.0149
0.0137	0.0148	0.0142	0.0149	0.0145	0.0131	0.0140	0.0131	0.0097	0.0139	0.0150
0.0121	0.0077	0.0122	0.0080	0.0143	0.0113	0.0141	0.0113	0.0102	0.0125	0.0117
0.0128	0.0092	0.0124	0.0066	0.0142	0.0132	0.0139	0.0132	0.0114	0.0145	0.0135
0.0123	0.0105	0.0115	0.0068	0.0127	0.0125	0.0124	0.0125	0.0122	0.0133	0.0119
0.0118	0.0103	0.0126	0.0089	0.0124	0.0115	0.0121	0.0115	0.0116	0.0133	0.0135
0.0114	0.0127	0.0119	0.0083	0.0116	0.0106	0.0113	0.0106	0.0108	0.0116	0.0089
0.0113	0.0111	0.0103	0.0085	0.0116	0.0112	0.0112	0.0112	0.0104	0.0120	0.0100
0.0127	0.0082	0.0123	0.0129	0.0145	0.0128	0.0142	0.0128	0.0108	0.0143	0.0107
0.0103	0.0082	0.0092	0.0073	0.0108	0.0108	0.0106	0.0108	0.0104	0.0119	0.0118
0.0107	0.0082	0.0099	0.0050	0.0117	0.0103	0.0115	0.0103	0.0103	0.0128	0.0120
0.0099	0.0083	0.0093	0.0051	0.0105	0.0096	0.0103	0.0096	0.0099	0.0120	0.0102
0.0136	0.0155	0.0136	0.0224	0.0140	0.0139	0.0134	0.0139	0.0092	0.0130	0.0144
0.0086	0.0084	0.0090	0.0058	0.0091	0.0077	0.0089	0.0077	0.0093	0.0090	0.0097
0.0086	0.0055	0.0086	0.0051	0.0102	0.0078	0.0100	0.0078	0.0081	0.0109	0.0088
0.0089	0.0065	0.0086	0.0039	0.0099	0.0080	0.0098	0.0080	0.0096	0.0116	0.0122
0.0134	0.0170	0.0147	0.0166	0.0135	0.0132	0.0129	0.0132	0.0094	0.0124	0.0105
0.0134	0.0069	0.0133	0.0201	0.0170	0.0132	0.0168	0.0132	0.0088	0.0150	0.0094
0.0108	0.0087	0.0098	0.0058	0.0122	0.0100	0.0120	0.0100	0.0086	0.0104	0.0132
0.0123	0.0089	0.0132	0.0156	0.0144	0.0122	0.0140	0.0122	0.0076	0.0115	0.0166
0.0134	0.0211	0.0140	0.0117	0.0127	0.0130	0.0121	0.0130	0.0103	0.0125	0.0121
0.0092	0.0085	0.0089	0.0075	0.0098	0.0091	0.0095	0.0091	0.0078	0.0089	0.0120
0.0134	0.0226	0.0139	0.0185	0.0125	0.0132	0.0119	0.0132	0.0098	0.0122	0.0114
0.0106	0.0137	0.0105	0.0144	0.0106	0.0107	0.0101	0.0107	0.0073	0.0100	0.0110
0.0122	0.0198	0.0116	0.0306	0.0117	0.0131	0.0110	0.0131	0.0064	0.0106	0.0110
0.0101	0.0058	0.0096	0.0113	0.0117	0.0107	0.0115	0.0107	0.0078	0.0115	0.0117
0.0107	0.0094	0.0104	0.0067	0.0115	0.0103	0.0112	0.0103	0.0100	0.0113	0.0107
0.0109	0.0125	0.0127	0.0137	0.0117	0.0100	0.0113	0.0100	0.0075	0.0102	0.0122
0.0125	0.0120	0.0139	0.0228	0.0141	0.0126	0.0136	0.0126	0.0064	0.0109	0.0121
0.0083	0.0052	0.0090	0.0056	0.0099	0.0075	0.0098	0.0075	0.0073	0.0090	0.0129
0.0095	0.0048	0.0106	0.0219	0.0125	0.0093	0.0123	0.0093	0.0055	0.0083	0.0112
0.0101	0.0061	0.0109	0.0166	0.0123	0.0102	0.0121	0.0102	0.0062	0.0103	0.0122
0.0107	0.0105	0.0115	0.0129	0.0113	0.0107	0.0109	0.0107	0.0084	0.0116	0.0121
0.0109	0.0123	0.0103	0.0274	0.0110	0.0114	0.0106	0.0114	0.0074	0.0100	0.0155

opt1 MLR	opt1 GAS	opt2 MLR	opt2 GAS	opt3 MLR	opt3 GAS	opt4 MLR	opt4 GAS	opt5 GAS	opt7 GAS	opt6 MLR	opt6 GAS
0.0095	0.0058	0.0103	0.0139	0.0115	0.0096	0.0112	0.0096	0.0062	0.0097	0.0123	0.013
0.0107	0.0122	0.0112	0.0111	0.0108	0.0105	0.0104	0.0105	0.0087	0.0106	0.0156	0.017
0.0130	0.0172	0.0132	0.0215	0.0130	0.0131	0.0124	0.0131	0.0090	0.0129	0.0151	0.016
0.0090	0.0072	0.0101	0.0117	0.0101	0.0084	0.0099	0.0084	0.0072	0.0093	0.0110	0.010
0.0082	0.0057	0.0083	0.0096	0.0094	0.0082	0.0092	0.0082	0.0060	0.0092	0.0142	0.017
0.0104	0.0087	0.0104	0.0090	0.0113	0.0098	0.0110	0.0098	0.0092	0.0127	0.0111	0.015
0.0109	0.0169	0.0100	0.0135	0.0104	0.0110	0.0099	0.0110	0.0081	0.0103	0.0114	0.012
0.0097	0.0084	0.0104	0.0087	0.0111	0.0088	0.0108	0.0088	0.0075	0.0107	0.0151	0.025
0.0068	0.0068	0.0076	0.0025	0.0070	0.0059	0.0069	0.0059	0.0091	0.0087	0.0148	0.017
0.0086	0.0073	0.0083	0.0076	0.0093	0.0080	0.0091	0.0080	0.0081	0.0103	0.0151	0.015
0.0098	0.0119	0.0094	0.0070	0.0096	0.0093	0.0093	0.0093	0.0098	0.0108	0.0125	0.014
0.0119	0.0213	0.0129	0.0384	0.0115	0.0119	0.0108	0.0119	0.0064	0.0094	0.0117	0.007
0.0150	0.0178	0.0145	0.0135	0.0149	0.0161	0.0142	0.0161	0.0105	0.0160	0.0102	0.005
0.0103	0.0114	0.0107	0.0108	0.0106	0.0101	0.0102	0.0101	0.0079	0.0108	0.0099	0.0131
0.0099	0.0110	0.0094	0.0144	0.0097	0.0106	0.0094	0.0106	0.0078	0.0113	0.0111	0.0154
0.0109	0.0113	0.0109	0.0101	0.0109	0.0113	0.0106	0.0113	0.0100	0.0128	0.0110	0.0147
0.0072	0.0067	0.0077	0.0028	0.0077	0.0058	0.0076	0.0058	0.0090	0.0088		
0.0109	0.0136	0.0119	0.0124	0.0114	0.0097	0.0110	0.0097	0.0086	0.0100		
0.0104	0.0108	0.0111	0.0134	0.0107	0.0109	0.0103	0.0109	0.0072	0.0104		
0.0094	0.0094	0.0093	0.0152	0.0100	0.0096	0.0096	0.0096	0.0061	0.0090		
0.0101	0.0099	0.0099	0.0148	0.0107	0.0104	0.0103	0.0104	0.0069	0.0102		
0.0101	0.0107	0.0105	0.0148	0.0106	0.0103	0.0102	0.0103	0.0065	0.0094		
0.0106	0.0149	0.0109	0.0176	0.0104	0.0113	0.0098	0.0113	0.0063	0.0107		
0.0097	0.0108	0.0105	0.0099	0.0099	0.0097	0.0096	0.0097	0.0075	0.0105		
0.0090	0.0084	0.0089	0.0047	0.0093	0.0085	0.0091	0.0085	0.0100	0.0105		
0.0106	0.0102	0.0102	0.0057	0.0110	0.0102	0.0107	0.0102	0.0108	0.0124		
0.0075	0.0106	0.0076	0.0039	0.0072	0.0068	0.0069	0.0068	0.0076	0.0076		
0.0092	0.0121	0.0086	0.0111	0.0090	0.0093	0.0086	0.0093	0.0066	0.0083		
0.0110	0.0186	0.0116	0.0215	0.0105	0.0110	0.0099	0.0110	0.0067	0.0091		
0.0103	0.0075	0.0107	0.0115	0.0116	0.0103	0.0114	0.0103	0.0079	0.0114		
0.0100	0.0114	0.0094	0.0132	0.0100	0.0101	0.0096	0.0101	0.0081	0.0103		
0.0100	0.0098	0.0102	0.0071	0.0103	0.0098	0.0100	0.0098	0.0099	0.0115		
0.0109	0.0116	0.0116	0.0152	0.0111	0.0111	0.0107	0.0111	0.0093	0.0113		
0.0117	0.0131	0.0117	0.0148	0.0116	0.0124	0.0111	0.0124	0.0087	0.0117		
0.0101	0.0111	0.0097	0.0149	0.0101	0.0107	0.0097	0.0107	0.0078	0.0097		
0.0110	0.0135	0.0111	0.0156	0.0108	0.0116	0.0103	0.0116	0.0081	0.0103		
0.0109	0.0110	0.0111	0.0078	0.0109	0.0117	0.0105	0.0117	0.0097	0.0117		
0.0142	0.0131	0.0138	0.0155	0.0148	0.0151	0.0143	0.0151	0.0105	0.0153		
0.0111	0.0125	0.0122	0.0135	0.0113	0.0104	0.0110	0.0104	0.0101	0.0110		
0.0140	0.0169	0.0138	0.0160	0.0138	0.0148	0.0132	0.0148	0.0104	0.0140		
0.0137	0.0159	0.0139	0.0262	0.0136	0.0143	0.0130	0.0143	0.0104	0.0154		
0.0075	0.0045	0.0089	0.0087	0.0088	0.0069	0.0087	0.0069	0.0080	0.0089		
0.0100	0.0103	0.0112	0.0081	0.0106	0.0094	0.0102	0.0094	0.0081	0.0096		
0.0128	0.0167	0.0140	0.0128	0.0128	0.0128	0.0123	0.0128	0.0090	0.0123		

opt1 MLR	opt1 GAS	opt2 MLR	opt2 GAS	opt3 MLR	opt3 GAS	opt4 MLR	opt4 GAS	opt5 GAS	opt7 GAS	opt6 MLR
0.0076	0.0080	0.0079	0.0046	0.0081	0.0067	0.0079	0.0067	0.0072	0.0080	
0.0100	0.0148	0.0095	0.0144	0.0096	0.0104	0.0091	0.0104	0.0064	0.0079	
0.0102	0.0120	0.0093	0.0119	0.0100	0.0105	0.0096	0.0105	0.0086	0.0097	
0.0093	0.0088	0.0090	0.0071	0.0093	0.0093	0.0091	0.0093	0.0099	0.0106	
0.0096	0.0085	0.0084	0.0036	0.0098	0.0094	0.0096	0.0094	0.0109	0.0115	
0.0106	0.0134	0.0108	0.0104	0.0106	0.0103	0.0102	0.0103	0.0086	0.0104	
0.0136	0.0241	0.0142	0.0398	0.0128	0.0149	0.0120	0.0149	0.0068	0.0108	
0.0134	0.0170	0.0146	0.0252	0.0133	0.0137	0.0127	0.0137	0.0093	0.0128	
0.0139	0.0148	0.0162	0.0333	0.0150	0.0140	0.0143	0.0140	0.0080	0.0123	
0.0113	0.0135	0.0108	0.0123	0.0115	0.0118	0.0110	0.0118	0.0074	0.0099	
0.0103	0.0133	0.0102	0.0068	0.0100	0.0104	0.0096	0.0104	0.0082	0.0093	
0.0107	0.0107	0.0100	0.0049	0.0108	0.0110	0.0105	0.0110	0.0098	0.0113	
0.0108	0.0070	0.0107	0.0110	0.0126	0.0105	0.0124	0.0105	0.0092	0.0118	
0.0093	0.0055	0.0094	0.0023	0.0108	0.0085	0.0107	0.0085	0.0113	0.0121	
0.0089	0.0077	0.0099	0.0053	0.0093	0.0083	0.0091	0.0083	0.0109	0.0117	
0.0089	0.0126	0.0100	0.0149	0.0086	0.0086	0.0082	0.0086	0.0071	0.0080	
0.0100	0.0148	0.0110	0.0161	0.0097	0.0094	0.0093	0.0094	0.0076	0.0086	
0.0099	0.0141	0.0114	0.0093	0.0096	0.0096	0.0092	0.0096	0.0078	0.0092	
0.0096	0.0077	0.0097	0.0034	0.0101	0.0094	0.0099	0.0094	0.0114	0.0123	

Chapter 5

Conclusions and Possible Extensions of Present Study

5.1 Conclusions

1. The equation devloped for prediction of %FeO by Genetic adaptive search gives better prediction of %FeO in slag as compared to multiple linear regression.

2. Although the best results of phosphorus prediction are obtained by using MLR (with a modified form of Healy's equation in which 'iron ore added' and 'volume of oxygen' blown in second blow are incorporated as additional terms), it is recommended to use GAS for phosphorus prediction for combined blown converters. This is because GAS gives correct sign of the coefficients of %CaO, $\log \%Fe_t$, and temperature (1/T) in Healy's equation.

5.2 Possible Extensions

1. It may be possible to further improve the prediction of phosphorus at end point by incorporating sublance data (C,T and P, in steel measured by sublance at dynamic control point).

2. A better estimate of %FeO in slag is needed by analyzing the slags at end point.

3. Some more variations of Healy's equation (with additional terms) can be tried.

4. It is necessary to analyse data of several campaigns and verify the equation obtained by GAS to see its general applicability. Only then the equation can be used on shop floor.

Bibliography

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